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14. Abstract

The recent AGARD Short Course on "Fundamentals of Fighter Aircraft Design", presented at the Von Karman Institute for Fluid Dynamics on February 17—21 1986, and in Greece and Turkey, considered the various aspects of aerodynamics. The present lecture series provides a general overview of the "state-of-the-art" in modern fighter design, with an introduction to the innovations of "Computer-Aided Design Evaluation" to both preliminary design and the final optimization of the various design compromises.

After the introduction reviewing the evolution of the modern fighter aircraft the Lecture Series will continue to develop the various stages of the total design problem. The integration of requirements into the preliminary configuration of the design will be followed by discussions of modern design techniques that are currently used to assess and validate the evolving configuration.

The second day will consider the overall integration process as applied to various current design challenges including multi-rôle aircraft, shipborne operator and VSTOL and STOVL concepts. The lecturers include two engineering qualified pilots who will contribute their experiences in development flying of several current single and twin engine fighters of both US and European origin. They will continue to present their perceptions of future military needs and resulting design trends.

All lecturers will contribute to a final Round Table Discussion.

This Lecture Series, sponsored by the AGARD Flight Mechanics Panel, has been implemented by the Consultant and Exchange Programme of AGARD.

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INTRODUCTION TO FMP LECTURE SERIES NO. 153 ON "INTEGRATED DESIGN OF ADVANCED FIGHTERS"

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ABSTRACT

The history and philosophy of aircraft design optimization will be briefly covered from the very beginning of the Wright Brothers first flight through some of the most anomalous aerodynamic design errors during both World Wars. It will be shown how either the lack of adequate theory, or the misuse of inadequate wind tunnel tests, led to the adoption of erroneous criteria for the optimization of fighter aircraft design.

The first example will show why the World War I fighter aircraft used very thin wing profiles because the wind tunnel tests were all conducted at too low Reynolds numbers. Then the improved design criteria that became available with both wind tunnel tests at higher Reynolds numbers, and the proper use of Prandtl's induced drag theory will be discussed.

The next examples will show how adverse compressibility effects were encountered during World War II as the flight Mach number increased during a steep dive. Again, adequate wind tunnel tests at higher Mach numbers were able to provide the solution to several problems. For example, the longitudinal control problems of "tuck under" and "elevator snatch" will be briefly discussed.

Then the severe problems of roll control for slender delta wing aircraft, and their inertia cross-coupling, will be introduced to show how analog and digital computer programs finally provided additional design tools that would in some cases surpasss the wind tunnel. Finally, it will be indicated how the advent of the high speed digital computer has completely revolutionized the design optimization of all aircraft.

INTRODUCTION

Prior to the wind tunnel tests made by Prandtl in 1915 at the University of Goettingen, the only available airfoil data was for Reynolds numbers considerably less than those attained in the actual flight of any man-carrying airplane. For example, the Wright Brothers' 1901 wind tunnel tests were performed with a one-inch (25.4 mm) chord airfoil at a maximum wind tunnel velocity of 27 mph (12.07 m/s), corresponding to a Reynolds numbers of only 20,000 whereas the actual Reynolds numbers of their first flights were all greater than one million. The Wright Brothers' wind tunnel tests showed that the maximum lift, and the lift-drag ratio, both increased as the airfoil was made thinner and the leading edge radius was decreased. Similar airfoil data, all at Reynolds numbers less than 70,000, were obtained in all of the wind tunnels prior to Prandtl's 1915 tests. Consequently all of the World War I fighter aircraft had very thin wings with a thickness ratio of only 6% or less, and a very sharp nosed leading edge. However, the Fokker D-7 was designed in 1917 on the basis of Prandtl's wind tunnel data which showed that as the Reynolds numbers approached one million the thicker airfoil with a larger leading edge radius developed a much greater maximum lift, and a better lift-drag ratio. Consequently, the Fokker D-7 had a 15% thick airfoil profile with 8% camber and a generously rounded leading edge, which resulted in excellent stall characteristics that permitted the development of new fighter aircraft maneuvers. For example, the Fokker D-7 was able to "hang on its prop" at very large angles of attack beyond the stall angle of attack, and it was found that this stalled position could be maintained by keeping the ailerons fixed and obtaining lateral control by quickly kicking the vertical tail rudder pedal so that the dropping wing tip would sweep forward and therby increase its lift due to both a decrease in the effective angle of attack and an increase in its relative velocity. This maneuver, and others resulting from its superior stall characteristics, made it the only aircraft demanded from the Germans by the treaty of Versailles. It is interesting to note that when the British captured their first Fokker D-7 in June 1918 they immediately made a 1/20 scale model of the wing and tested it at Reynolds numbers less than 70,000 and decided the thicker wing profile had been used for structural strength, and definitely not for any aerodynamic superiority.

This first example shows how important it is to define the physical properties of any aerodynamic component before it can either be optimized, or studied mathematically. If, for example, an optimum airfoil for performance at Reynolds numbers less than 70,000 was desired, then only wind tunnel tests, and not CFD (Computational Fluid Dynamics), would provide the answer if the physical characteristics of this relatively low Reynolds number flow were not known. Experimental flow visualization has shown that instead of the expected laminar separation a sharp leading edge at these low Reynolds numbers sheds small discrete vortices; consequently the usual finite difference, or finite element CFD should not be applied to this problem, instead the Discrete Vortex Method developed by Chorin (ref. 1) is numerically more efficient. Unlike finite difference methods which would require an extremely small mesh to describe this type of leading edge flow, the vortex method of Chorin is capable of resolving multiple length scales and is devoid of numerical instabilities as the Reynolds number increases. Furthermore, it maintains computational efficiency by partioning small regions of high fluid shear into arbitrarily small computational elements (ref. 2).

Although the behavior of the zero lift drag has been well established at nearly all Reynolds numbers, the corresponding effects of finite lift were not well understood at Reynolds numbers less than 70,000 (ref. 3) until a series of finite aspect ratio thin wings were tested in the University of California low turbulence wind tunnel (turbulence level 0.02%, ref. 4). Figs. 1 and 2 confirm the Wright Brothers wind tunnel results that both the maximum lift and the lift-drag ratio are better with a thin flat plate than they are with a typical airfoil profile (NACA 0012), and are further improved if the thin flat plate is curved to form a circular arc with 5% camber. Increasing the turbulence level to nearly one percent had very little effect on the thin plates but decreased the performance of the NACA 0012 airfoil as indicated by the dotted line in Fig. 1 which is now similar to airfoil data obtained in typical high turbulence wind tunnels, as in ref. 3, and by the Wright Brothers. The surprising jump in lift starting at 3° angle of attack is due to both the low turbulence level, and the rather sharp leading edge of this relatively thin airfoil shedding discrete leading edge vortices. These prevent the laminar separation that is indicated by the dotted line data obtained at high turbulence levels. The shedding of the leading edge vortices by a flat plate was the same with either a square leading edge, or a knife blade sharp leading edge, as long as the plate thickness was less than 2% of the chord at Reynolds numbers less than 70,00.

In order to define the physical characteristics of this sharp leading edge vortex shedding the surface static pressure measurements on a flat plate are presented in Fig. 3. It is evident that this low Reynolds number flow is entirely different from previously analyzed aerodynamics. First the usual Kutta-Joukowsky condition is not satisfied at the trailing edge. Secondly the stagnation point is at the sharp leading edge, at least up to the stall angle of attack, since Fig. 4 shows that the stagnation point does not move aft to the 1.3% chord location on the lower surface until the angle of attack is 24°. This proves that this flow is entirely different from the classical Kutta-Joukowsky potential flow aerodynamics, or the fully separated wake flow of the Rayleigh-Kirchhoff theory, both of which have the stagnation point well below the leading edge. Consequently, conventional CFD could not be applied until these anomalous flow characteristics are taken into account. Of course, this analysis would only be useful for explaining the flight behavior of small birds and flying insects, and not that of any man-carrying aircraft. However, it provides a useful example of the pit-falls inherent in any CAD system that does not carefully evaluate all of the pertinent physical characteristics involved.

Another example arises from a re-evaluation of Prandtl's induced drag theory that minimized the induced drag for monoplanes, biplanes and even the triplanes of World War I (ref. 5). This theory showed that any airplane having its horizontal tail in the plane of the wing would have its total induced drag be a minimum if the tail had zero lift (ref. 6). Later it was shown that a high or low tail position could have minimum induced drag only if the tail carried a positive lift (ref. 7), the same result, as shown by Munk (ref. 8), applies to a front lifting canard surface. Now the future transonic transport aircraft are being designed by a CAD system that assumes the optimum transonic wing is that which has the least compressibility drag rise at cruise speed. However, these "optimum transonic wings" unfortunately have an extremely large nose down pitching moment that can only be balanced by a large tail download for any stable center of gravity location. In some cases this leads to a down tail load equal to 10% of the gross weight so the wing must carry 110% of the gross weight. This additional trim-load drag could be greatly reduced by considering the over-all drag in the optimization of the airfoil profile at the start. That is the trim drag due to an undesirable tail down load must be balanced with the drag rise due to compressibility effects at the initial phases of the CAD, rather than after an undesireable wing has already been preselected.

In World War II several adverse compressibility effects were produced by the higher flight Mach numbers attained in a steep dive. One of the first was encountered by the P-38 fighter airplane shown in Fig. 5. Because of the greatly increased local velocities on the wing section between the fuselage and the engine nacelles, a supersonic shock wave formed on this portion of the wing even though the airplane's actual flight Mach number was quite subsonic. This local shock wave caused flow separation and a decrease in the wings downwash flow angle acting on the tail. Thereby the longitudinal stability term $(1 - \varepsilon_\alpha)$ was so greatly increased (see Fig. 5) that the airplane became so stable that the maximum elevator deflection could not produce enough nose-up moment to pull the airplane out of its steep dive. The solution to this P-38 dive problem was obtained by the NACA wind tunnel tests described in ref. 9.

Also in World War II several fighter airplanes developed a nasty behavior of suddenly either greatly increasing, or reversing the "stick force" operating the elevator deflection. This was aptly termed "elevator snatch" since it seemed to abruptly force the elevator control stick out of the pilots' hands. This adverse behavior was produced by a dive at sufficiently high subsonic speeds so that a local supersonic zone was produced at the leading edge of any elevator that had its frontal surface protrude into the free stream above, or below, the elevator surface. Before these high Mach number effects were encountered, it was believed that such a blunt nosed elevator design was a satisfactory method for reducing the elevator hinge-moment. Again wind tunnel tests were able to correct these design errors only when the Mach number was at full-scale, and the Reynolds numbers (which was impossible to duplicate full-scale) was greater than one million.

Towards the end of World War II it was found that during a rolling pull-out maneuver a slender fuselage fighter airplane could develop a yawing moment that produced sufficiently large sideslip angles that in certain cases could produce a vertical tail failure. This maneuver could not be predicted by the conventional linearized equations so in 1948 Phillips (ref. 10) used fourth-order nonlinear equations that explained the crucial effects of inertia cross-coupling during a constant rolling maneuver. Phillips' analysis was the first to show that for any slender fuselage (i.e. inertially slender about is roll axis) there could be a critical roll rate that produced dangerous pitching and yawing oscillations. Rhoads and Schuler (ref. 11) then used fifth-order nonlinear equations to show that both inertial and aerodynamics nonlinearities must be included in order to provide an order of magnitude estimate of the state variables in any cross-coupled rolling maneuver. Pinsker (refs. 12 and 13) showed that under certain circumstances a fast-rolling inertially-slender airplane could autorotate in roll after the ailerons had been returned to neutral. Pinsker also found that this type of airplane at moderate angles of attack tended to roll about its principal axis of inertia. By solving the fifth-order nonlinear equations (shown in Table I) on a digital computer using the Runge-Kutta method Walsh (ref. 14) found that aileron angles which produced rates of roll near the natural frequencies of the non-rolling aircraft resulted in undesirably large magnitudes of the sideslip and pitch. Davari and Laitone (ref. 15) then used Walsh's method to show that a linear decrease of $C_{m\alpha}$ with α introduced two additional critical aileron deflections that produced violent oscillations during a roll maneuver. Now, as will be pointed out in this lecture series, the modern high-speed computer programs can solve the complete nonlinear equations of motion. However it must be noted that although the inertia terms can be accurately calculated, still the aerodynamic terms can only be estimated from the careful application of many wind tunnel tests, and the highly sophisticated mathematical use of theoretical aerodynamics. As in our first example of aerodynamic lift at Reynolds numbers less than 70,000, the application of CFD to evaluate the aerodynamic terms in the rolling pull-out study would be critically dependent on a thorough understanding of the physical behavior of the ensuing air flow. For example, the variation of the strong vortex formed at the fuselage juncture with a delta wing would provide the primary consideration as to which CFD procedure should be used.

An excellent description of the benefits obtained from the introduction of CAD, CADE, and CAM to the development of the McDonnell-Douglas F-15 fighter airplane is given in ref. 16. The CAD-CAM discussion concluding this introduction is based on the Dassault-Brequet Aviation motion picture film on the development of the Mirage 2000 jet fighter.

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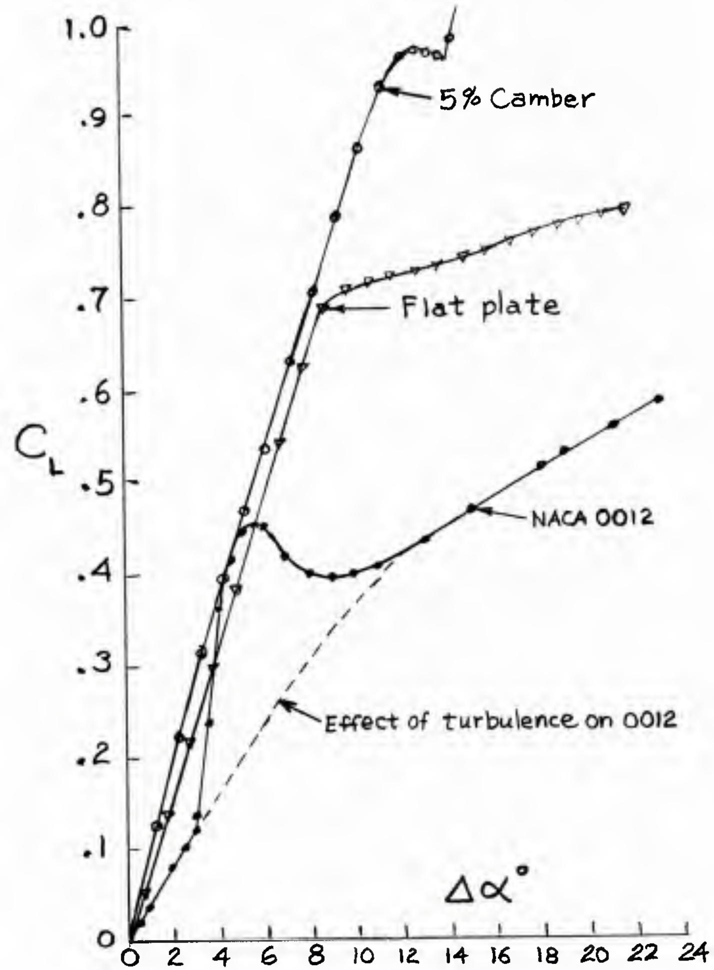

Fig. 1: Aspect ratio 6 at R_e = 20,700.

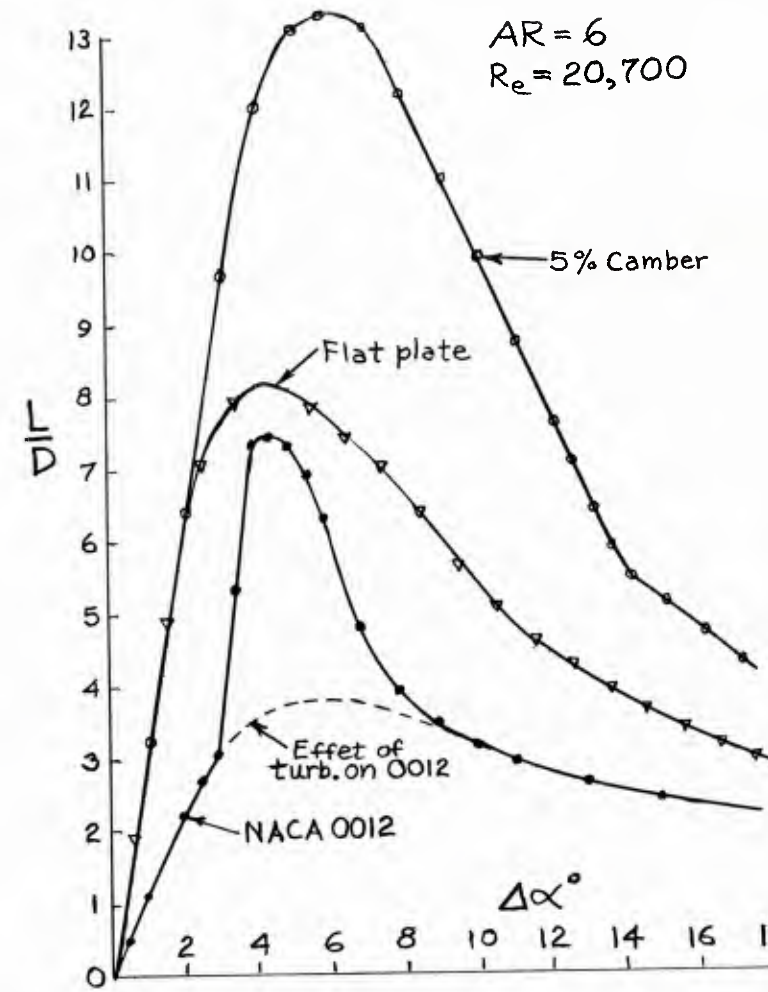

Fig. 2: L/D corresponding to Fig. 1.

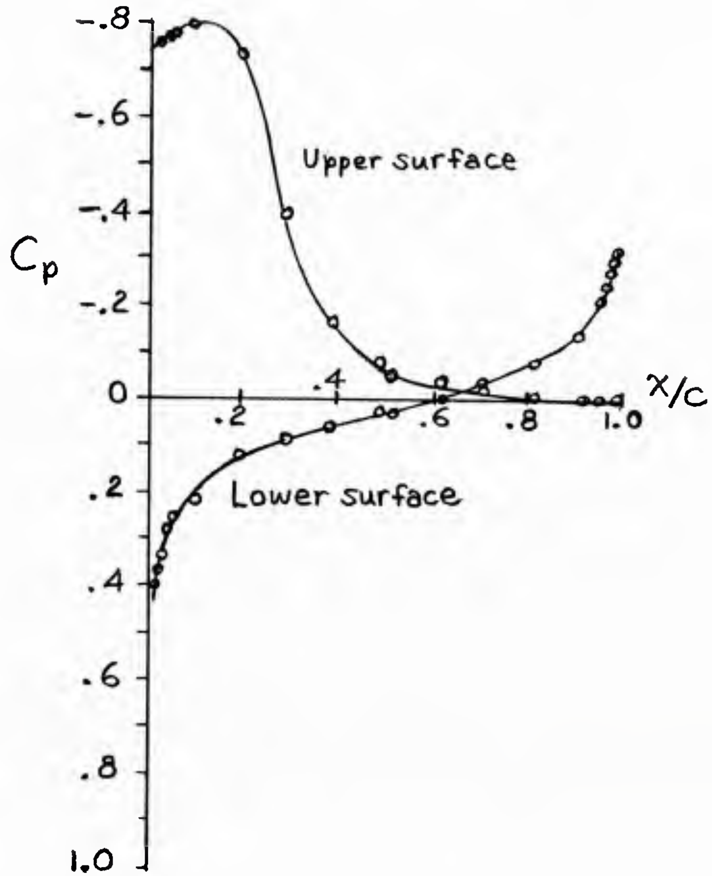

Fig. 3: Pressure distribution on a flat Plate with AR = 6.

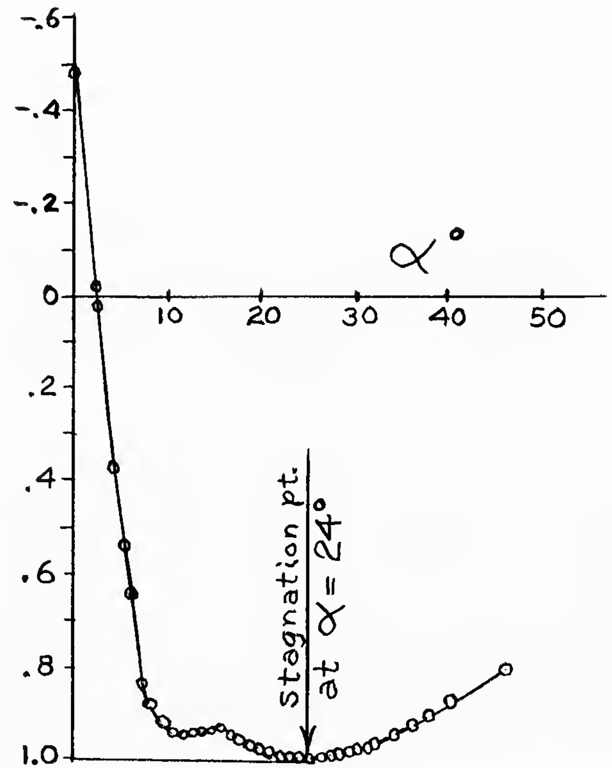

Fig. 4: C_p at 1.3 % chord.

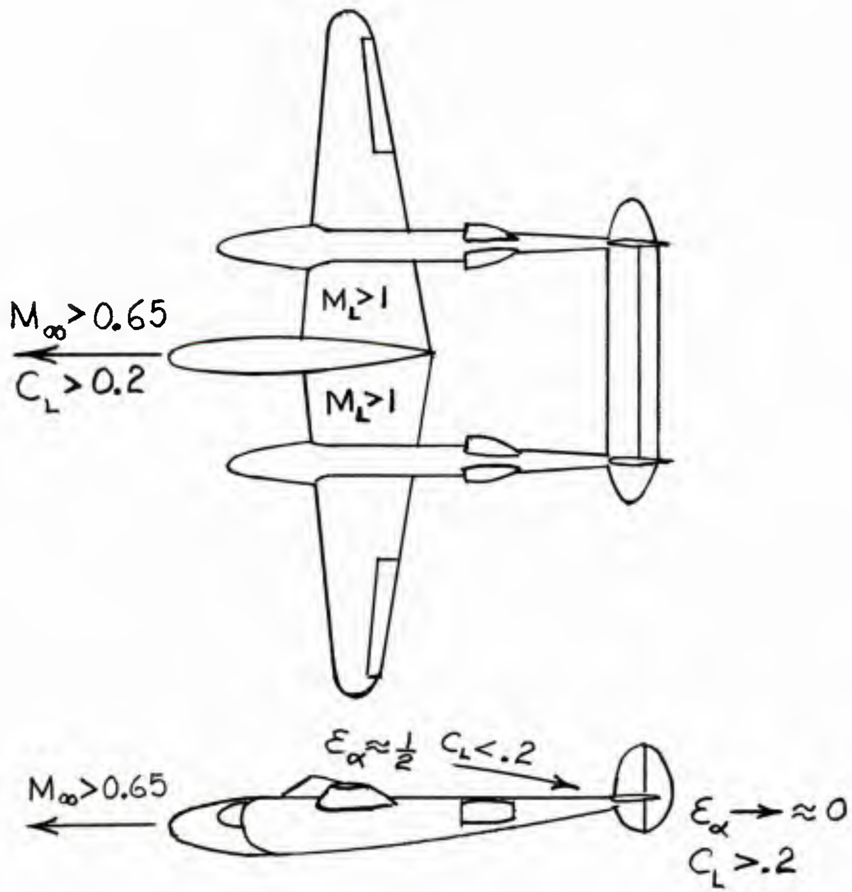

Fig.5: P-38 in a dive producing a local supersonic flow on wing upper surface.

Table I : Nonlinear equations for the study of aileron forced autorotation.

$$\mathring{v} \approx p w - r$$
$$\mathring{w} \approx -p v + q + z_w (w - w_0)$$
$$\mathring{p} \approx l_v v + l_p p + l_\xi \xi$$
$$\mathring{q} \approx -\left(\frac{I_x - I_z}{I_y}\right) p r + m_w (w - w_0)$$
$$\mathring{r} \approx \left(\frac{I_x - I_y}{I_z}\right) p q + n_v v$$

where w_0 is the initial angle of attack of the principal axis (X) so that :

$$w_0 = (W_0 / V_\infty) = \tan^{-1} \alpha_0 \approx \alpha_0$$

$$m_w = m_w(0) + (\partial m_w / \partial w) w, \quad \text{(ref. 15)}$$

The remainig aerodynamic derivatives are constant for the principal axes (I_x, I_y, I_z) during roll (p) produced by ξ aileron deflection.

INTEGRATION OF AERODYNAMIC, PERFORMANCE, STABILITY AND CONTROL REQUIREMENTS INTO THE DESIGN PROCESS OF MODERN UNSTABLE FIGHTER AIRCRAFT CONFIGURATIONS

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1. ABSTRACT

Already in the early design stage of a modern fighter aircraft development with usually unstable basic characteristics in pitch, a well balanced compromise between optimum performance and excellent handling qualities has to be found. This compromise must be based on sufficient margins for stability and control, manoeuverability in terms of agility and economic aspects which usually are in contradiction to pure performance requirements as for example sustained/instantaneous turn rates and high specific excess power.

In this paper reasonable criteria deducted from flight mechanical and control law design point of view are discussed, which lead straight ahead towards a set of desirable longitudinal and lateral characteristics for the basic unaugmented aircraft. These requirements impose remarkable constraints for the aerodynamic design of a fighter and its elements like wing planform, strakes, vertical fins and horizontal tail size and location. The problems and possibilities to stay within the reasonable flight mechanical limits are demonstrated.

2. INTRODUCTION AND JUSTIFICATION FOR UNSTABLE DESIGN IN PITCH

Extremely high requirements in terms of performance and handling qualities throughout an extended flight envelope lead to the conclusion that in modern fighter aircraft design the consequent use of ACT (active control) and CCV (control configured vehicle) technologies is an absolute compulsary thing to do. Task tailored handling characteristics, care-free-handling features and the implementation of automatic functions and control modes usually offer such remarkable benefits for an optimum mission capability that they outweigh penalties of such a design like larger actuators with high power consumption, high sensor performance, redundant flight control system and high requirements for the computer speed and capacity (Fig. 1).

The choice of longitudinal instability as a further mean to gain some more advantages in the field of performance and manoeuverability turns out to transform this beneficial technology into a very sensible balance. Increasing complexity in the flight control system (FCS) which now not only ought to augment but really has to guarantee stability, tends to drive the pendulum of the balance to the unfavourable side if adverse basic characteristics of the configuration in combination with a too high instability level amplify the burden on the FCS.

Keeping this risk in mind it is advisable to analyse very carefully those areas within the design flight envelope where particularly instability can help to improve the performance and manoeuverability of the aircraft. Fig. 2 illustrates a typical dogfight situation in a turn-rate/Mach-number diagram. During the engagement phases of acceleration and deceleration keep changing in a certain circle. The main combat region is defined by the lines of maximum 'g'-capability and maximum usable lift which meet at the so-called 'corner speed', whereas the acceleration and deceleration zones are given by the sustained turn rate limits of the aircraft. It is evident that the opponent with the higher usable lift, the smaller turn radius capabilities and the higher sustained turn rates will have remarkable advantages and will be likely to win the fight. In this connection it should be mentioned that an increase of the maximum load factor itself to higher than '9 g' may not be possible because the physiological limit of the human pilot seems already to be reached by this value. So pushing the maximum load factor limit towards lower Mach numbers should be a more promising direction of optimization. Furthermore an improvement in terms of agility near and even beyond stall, as pointed out in Fig. 3, in connection with excellent handling qualities in this region should be a major point of interest in future fighter design. Short range combat simulations have shown that a quicker controlled change of angular rates and attitudes at low dynamic pressure and high angles-of-attack offers to the pilot increased possibilities to get in advantageous positions.

In the high Mach number/altitude region exists another area within the flight envelope where, especially in medium-range-combat situations with missiles, improvements in performance in comparison to existing fighters are of major interest. Translated into requirements, higher sustained turn rates and higher specific excess power are the main design goals in this high Mach number range.

This small summary of future fighter design goals leads, if transferred into aerodynamic and flight mechanical characteristics, to rather contradictory requirements. The supersonic design aims demand 'clean' configurations with small span and wing area because low zero-lift drag is the necessary basis for increased sustained performance data. At subsonic speeds a high wing/tail-efficiency resulting in low induced drag, high maximum lift and a good basic behaviour at high angles-of-attack is needed. This normally requires larger span, a larger wing providing maximum lift and a careful optimization of the configuration especially in the wing apex zone.

A suitable tool to overcome some of the contradicting requirements is the introduction of unstable design in pitch which has remarkable effects on performance as demonstrated in Fig. 4. The trim characteristics of the sample aircraft (i.e. a tailless configuration; the principals apply for any tailed configuration as well) show that the stable version will have negative slopes in the pitching moment-lift diagram for controls fixed. Therefore it is necessary to trim the configuration with negative (i.e. upwards) flap deflections. An unstable design with the centre of gravity aft of the aerodynamic centre, has a positive $\partial C_m/\partial C_L$ (and $C_{m\alpha}$) slope and therefore requires positive (i.e. downwards) flap settings for trim. The sketch of the polars in the lower part of Fig. 4 shows the resulting beneficial effect on trimmed performance data: Typical supersonic fighter wings are characterized by a relatively small aspect ratio and high leading-edge sweep. Especially for those the induced drag for a given lift coefficient is much smaller with positive than with negative flap deflections. This leads on one hand to a remarkable reduction in overall drag at a desired turn rate and on the other to a much larger trimmed maximum lift coefficient. If the full technically feasible potential of unstable design is used, then relative to a conventionally stable aircraft maximum lift can be increased by roughly 25 % and induced drag at a typical lift coefficient for manoeuvre (say $C_L \approx 0.7$) can be reduced by about 20 %. This means that unstable configurations when designed for the same performance requirements and under the same flight mechanical constraints, will be remarkably smaller than their stable 'brothers' as shown in Fig. 5. A reduction in combat mass (including internal fuel) of about 18 %, a smaller required thrust of about 16 % and a reduction in wing area of about 18 % can be achieved as demonstrated by detailed studies.

Thus artificial stabilization of a basicly unstable aircraft is a very attractive feature to find reasonable solutions for the increased requirements. But there are lots of criteria and margins derived from flight mechanical and control law aspects, which restrict the level of instability so far that the aerodynamic 'optimum' (i.e. minimum drag and maximum lift) may not be achievable.

3. FLIGHT MECHANICAL PROBLEM AREAS AND DESIGN REQUIREMENTS FOR THE BASIC PITCH CHARACTERISTICS

A general summary of possible problem areas within the pitch characteristics of unstable designed fighter configurations is given in Fig. 6. The typical C_m versus α plots containing the curves for 'zero' and 'full nose down' controls point out that one limiting factor for unstable design will be given by the definition of a necessary pitch recovery moment which above all has to guarantee a safe return from high angle-of-attack manoeuvres. The basic design instability covering only performance aspects, will usually be chosen at low and medium angles-of-attack. This instability has to be checked against the capabilities of the flight control system. The same applies to the allowable pitch-up at higher angles-of-attack in trimmed conditions. It depends on the chosen configuration and may introduce a lot of unwanted $C_{m\alpha}$ beyond the basic value. In addition the behaviour of the three critical values versus Mach number should be considered very carefully.

3.1 Necessary Pitch Recovery Moment

The minimum pitch recovery control power which has to be installed at high angles-of-attack near C_{Lmax} can not only be defined by sufficient nose down acceleration which has to provide a safe return from manoeuvres near stall. A more detailed analysis of the problem leads to the conclusion that the required nose down control power can roughly be split into two parts:

1) basic demand for stabilization, for counteracting gusts and for sufficient pitch handling qualities during high angle-of-attack manoeuvres

2) additional control power for increased agility at high angles-of-attack.

The basic demand which has to be provided in the nose-up as well as in the nose-down direction is a matter of experience and cannot be deducted precisely by mathematical equations. As a rule of thumb the required pitch acceleration could be fixed at about $\ddot{\theta} \approx \pm 0.3$ rad/s². This margin which should be designed for in any case, is supported by several simulation studies and recent work within several fighter projects.

Additional pitch control power for increased agility at high angles-of-attack is directly combined with the requirements for maximum roll rate in this region. The sketch on top of Fig. 7 shows that any roll rate around the velocity vector is combined with a pitch-up moment. The aircraft acts like a dumb-bell and the resulting inertial coupling produces a nose-up acceleration which is given by:

$$\ddot{\theta}_{iC} = \frac{1}{2}\, p_V^2 \cdot \sin 2\alpha$$

So beneath the basic recovery margin additional pitch down control power is needed to counteract the inertial coupling during roll manoeuvres. As soon as the angle-of-attack for maximum lift (i.e. roughly the location of minimum nose down control power) is known it is possible to draw a design chart of required pitch down acceleration versus roll rate, as shown in the lower part of Fig. 7. The fix of a roll rate requirement at a certain calibrated airspeed leads us straight forward towards the nose down recovery margin in terms of $\ddot{\theta}$ or pitching moment coefficient ΔC_{mRec} which has to be installed. It is important to point out that a certain loss in pitching moment due to differential flaps has to be taken into account; this leads to the slightly transverse line in the design chart if the recovery moment is defined to be derived from the configuration with all pitch controls deflected fully down.

Fig. 8 shows again a principal comparison between the pitching moment characteristics of a stable and unstable configuration versus angle-of-attack. Once the necessary corridors for pitch control power are settled as discussed before, it gets evident that the trend of available control power versus angle-of-attack and the trend of requirements will fit better when using a stable design.

For a more and more unstable configuration the necessary nose down recovery moment becomes a critical value. Therefore the recovery margin sets one important limit to basic instability level.

3.2 Maximum Basic Design Instability

Unfortunately it is still common use to highlight the static margin, $SM=-C_{m\alpha}/C_{L\alpha}$, as the only important characteristic value which describes all the problems and difficulties connected with the artificial stabilization of an unstable designed aircraft. In reality the control power needed for stabilization as well as for the installation of excellent handling qualities depends on much more factors as for example moment of inertia, natural damping, wing area, aerodynamic chord and dynamic pressure. All these parameters contribute to a 'Time to Double Amplitude', T_2, during which, with controls fixed the aircraft will double a distortion in angle-of-attack. In combination with available control power and the possibilities of a rapid control power build-up the 'Time to Double Amplitude' enables the specialists to judge if a chosen aerodynamic instability level is feasible or not. Fig. 9 shows in detail that at constant Mach number and altitude four different configurations with four different design instabilities (SM = -8 % to -20 %) may have a T_2 which lies in the same order of magnitude. Thus the dynamic problems, associated with the stabilization of the four configurations should not be too far apart.

In practice it is of course necessary that the control law people and the aerodynamisists can communicate and understand each other in order to end up with a well balanced design. So once the dynamic limit of unstable design in terms of T_2 has been defined it has to be translated into aerodynamic characteristics like $C_{m\alpha}$, $C_{L\alpha}$ or SM. To give a rough feeling how the dynamic instability can be correlated with data that is common to an aerodynamic specialist, the headline of Fig. 9 presents a formula which should be sufficient for a first guess during preliminary design:

$$T_2 \approx \frac{\operatorname{arc\,cos\,h}\,(2)}{V \cdot \sqrt{\dfrac{C_{m\alpha} \cdot \rho \cdot S \cdot \bar{c}}{2\, m \cdot iy^2}}}, \qquad SM = -\frac{C_{m\alpha}}{C_{L\alpha}}$$

Fig. 10 shows 'Time to Double Amplitude' T_2 versus Mach number for an arbitrary tailless configuration having a basic design instability of SM = -10 % in the low angle-of-attack/low Mach number region. By analysis of the T_2 trend versus Mach two principal problem areas can be identified:

- At higher subsonic Mach numbers the T_2 approaches a minimum value before the aerodynamic centre starts to shift aft and tends to stabilize the configuration. In this area the time delay budget within the control system will set the limits for identification of the maximum design instability.
- In the low Mach number range T_2 will be remarkably larger and at first glance the problems for stabilization seem to relax. The discussion in chapter 3.3 will show that fading control power and pitch-up tendencies at high angles-of-attack may lead to additional limits.

Every existing control system using sensors, filters, computers and actuators will produce a number of parallel or subsequent time lags and time delays which influence the ability to stabilize an unstable system. If in addition the basic dynamic characteristics of the system to be controlled, turn out to have a very small Time to Double it may be impossible to end up with the necessary quality and safety margins or with a stable behaviour itself. One can imagine that if Time to Double and effective Time Delay should happen to be in the same order of magnitude even an excessive enlargement of control power or control power build-up rate would not be sufficient to get a system with satisfactory stability and handling qualities.

Fig. 11 shows a summary of characteristic time delays and time lags which are normally contained in a (rather complex) flight control system. If we concentrate on the more important righthand side of the figure where the several time delays are highlighted, the whole budget adds up to about 40 milliseconds. Some of the time delays like air data and inertial sensor computing and filtering produce parallel shares to the total budget while others like transport, voting and monitoring have to be handled as subsequent events.

Fig. 12 now presents the results for the definition of maximum design instability or better: minimum allowable Time to Double, T_2. Based on a stable aircraft as unity the required control acceleration, which is roughly equivalent to the required hydraulic power, is plotted versus T_2. The aspects which are covered in this plot contain safety considerations (phase and gain margins) as well as handling quality aspects (gusts, transients). The stable configuration as a standard was chosen, because even in this conventional region a basic level of control power build-up rate is needed to ensure good flying qualities. Following the trend of the curves in Fig. 12 the required control acceleration is a hyperbolic type function of T_2. The time delay budget which has been discussed before, turns out to be an important parameter especially at high dynamic instabilities. Below a T_2 of about 6 x T_t the gradient of the control power requirement gets so steep that only a small error in preliminary design towards the unfavourable direction will lead to enormous additional hydraulic power demands. So it seems to be reasonable to stay well above this margin. Considering the technical standard of today ($T_t \approx 0.04$ s) leads us to a recommended value of minimum Time to Double

$$T_{2min} \gtrsim 250 \text{ ms}$$

which should be a feasible limit at high dynamic pressure (Ma ≈ 0.9, SL) for settling the allowable design instability (SM) during preliminary stages of a fighter project.

3.3 Pitch-up Tendencies

The technical limit of maximum design instability derived up to this point does not describe all critical aspects of an unstable aircraft. As mentioned above pitch-up tendencies will be of some importance. A senseful limit of pitch-up within the whole Mach number range can be evaluated by handling and ride quality aspects. This will be discussed in a relatively simple way with respect to the so-called CAP-parameter and the gust response.

CAP-Parameter

Roughly spoken the CAP-parameter (Control Anticipation Parameter) describes the aircraft behaviour after a step input in pitch stick in terms of required 'g'-onset $\dot{n}_{Req}$ and steady state load factor n_{St} (Fig. 13). Excellent handling qualities (LEVEL 1*) are characterized by a reasonable time t after which n_{St} is reached. Furthermore no excessive overshoots above or oscillations around the steady state load factor are allowed which implies a damping ratio ζ of about 0.6 to 0.8.

Analysing the CAP-parameter one can idealize the curve shown in the figure by some e-function having a time delay of $T_{\Theta 2}$. More generally spoken the essential parameters defining CAP can be derived as:

$$CAP = \omega_{osp}^2/(n/\alpha) \text{ or}$$

$$CAP \approx g \cdot \frac{X_{a.c.} - X_{c.g.}}{iy^2} \quad [1/s^2]$$

This means that the CAP-parameter directly defines a certain 'effective stability' depending on fuselage length (which mainly defines the radius of inertia in pitch). Therefore the flight control system needs something like an α feedback in order to transfer the unstable $C_{m\alpha}$ into a stable one, which is illustrated in the plot $C_{m\alpha}$ versus α in Fig. 14. If there is a local pitch-up zone in some high α region (normally around or slightly below the α for C_{Lmax}), two aspects have to be taken into account:

- Without gain scheduling of the α feedback versus angle-of-attack the aircraft tends to leave the LEVEL 1* zone and handling qualities are reduced.

- If the gains are scheduled according to local $C_{m\alpha}$, additional control power is needed for stabilisation. Furthermore the pitch-up zones extend over a relatively small α range (say $\Delta\alpha \approx 5° \div 10°$) with possibly abrupt changes in $C_{m\alpha}$ versus α. This demands sufficiently accurate α sensors for gain scheduling. Therefore the required smoothness of the C_m versus α curve is a direct function of sensor accuracy.

In general a highly augmented aircraft reacts differently on $C_{m\alpha}$ variations than an unaugmented one. The plot in Fig. 15 shows the root location of the short period motion, typical for a conventionally stable configuration. Having selected an undamped frequency ω_{osp}, defined by the CAP-parameter, and a required damping, the design aim of the aircraft is fixed. On the ordinate of the root-locus plot one can find the damped frequency ω_{Dsp} and on the real axis the value for damping times frequency $\zeta \cdot \omega_{osp}$. Frequency is a direct function of stability (plus a minor term) but $\zeta \cdot \omega_{osp}$ is not. So pitch-up decreases frequency and increases damping, an effect which reduces agility but is not dangerous as long as pitch-up is kept within certain limits.

A highly augmented aircraft usually shows a different behaviour (Fig. 16): Instead of the simple two roots describing the short period of an unaugmented configuration, the short term motion is now influenced by a lot of further roots, produced by sensors, filters, actuators etc. At first glance it seems to be difficult to derive the behaviour of the aircraft from all these roots. A common procedure to solve the problem is to analyse the Bode-diagram and try to find an equivalent pair of roots which describes the complex behaviour with sufficient accuracy.

In this equivalent system however a pitch-up produces different effects. A typical trend presented in the figure shows a rapid reduction of dampig. This results in larger overshoot and oscillation tendencies which finally make precise tracking manoeuvres impossible.

As far as the pilot's input is concerned a too large $C_{m\alpha}$ can be coped with a forced reduction in maximum possible 'g'-onset, provided by a command shaping filter. The resulting lower CAP-parameter, however will lead to a degradation in agility within the affected angle-of-attack range below C_{Lmax}.

Gust Response

As stated above command shaping is in principle possible to overcome a certain amount of pitch-up; but inputs which cannot be 'shaped' by the FCS are gusts. Especially gust ramps which usually occur in large thermal upwind regions or in mountains (shear wind) have to be considered more carefully in connection with an unstable aircraft.

Fig. 17 shows the results of a simple simulation for a typical (canard) configuration entering a 20 m/s vertical gust ramp at higher incidences (i.e. $\alpha \approx 20°$). A maximum deflection rate of the pitch control device of 70°/s and an overall time delay of 60 msec have been assumed to be representative. The trailing-edge flaps have been deflected according to optimum performance so that besides a certain reserve for roll control no additional pitch-down potential could be produced. Airspeed has been set to 160 m/s which corresponds roughly to the corner speed; thus the simulation was done well within the normal manoeuvre range of $n \approx 6$ g and $\alpha \approx 20°$. The only parameter which is exceptional , is the $C_{m\alpha}$ which has been increased by twice the value of basic instability level.

The figure shows the gust upwind w_{GUST}, control deflection of the canard, the pitch rate, and the load factor Δn versus flight distance.

The maximum upwind of 20 m/s is reached after a flight distance of 35 m. 60 milliseconds after the gust onset the pitch control device (canard) begins to move with its maximum deflection rate in order to stabilize the gust. As a consequence of the too high instability the FCS cannot balance the nose-up acceleration at once in spite of the fact that the controller has reached its saturation speed. Hence a pitch rate is built-up, and a lot of time is needed to cancel its energy.

Contrary to that a stable aircraft tends to counteract the gust by itself, because the center of gravity is in front of the aerodynamic center. So a gust upwind will result in a nose-down pitch rate, and additionally the pilot has the full control power available to take further actions.

The maximum load factor is not very different for both aircraft, but the unstable one retains this high load factor for relatively long time. At the same time the angle-of-attack remains constant so that even a relatively small α range with a high pitch-up can have large effects: The aircraft tends to enter something like a looping.

More detailed calculations showed that the situation is aggravated by the fact, that drag is increased by the increased α. Thus the aircraft decelerates and control power is reduced because of lower dynamic pressure, meanwhile the rotational energy remains the same.

This simple simulation demonstrates that even in the low-speed region gusts can become critical. It has to be guaranteed, that for a 'critical designing gust' maximum deflection rate of the controls is not reached or only reached for a short time so that the pilot has at least some control power left.

Once such a gust has been defined the question arises what air speed is most critical. Assuming same gust upwind and knowing the maximum deflection rate $\dot{\delta}_2$ at some speed V_2 one can relatively simply estimate $\dot{\delta}_1$ for a different speed V_1 by the formula shown in Fig. 18. In the diagrams on top the instability versus Mach number is plotted: on the left side expressed in $C_{m\alpha}$ and on the right side in T_2. The T_2-criterion which has been derived above for high-speed is marked at Ma = 0.9. The curves A represent typical values of low-α instability versus Mach number. At transonic speeds the aerodynamic center shifts aft and $C_{m\alpha}$ becomes less unstable. The curves B indicate the trend of allowable instability under the assumption that $\dot{\delta}_{max}$ and $C_{m\delta}$ are no function of Mach number and dynamic pressure Q. For $C_{m\delta}$ this might be correct because of aeroelasticity, but $\dot{\delta}_{max}$ is in most cases a function of Q. The curves C represent the limits regarding this effect. The figure shows that the sample configuration is critical for low α at Ma ≈ 0.7 and not at Ma = 0.9 where the T_2-criterion was defined. At low speeds a certain amount of pitch-up is allowed (≈ 20 % to 40 % of basic SM) depending on details of the configuration.

Of course in reality conditions are somewhat more complicated but the deduction above already shows reasonable trends and the order of magnitude one has to account for.

4. FLIGHT MECHANICAL PROBLEM AREAS AND DESIGN REQUIREMENTS FOR BASIC LATERAL/DIRECTIONAL CHARACTERISTICS

Considerations about requirements for the lateral/directional basic characteristics of a modern fighter design have to start with the evidence that an unstable design in roll/yaw will not lead to such remarkable gains in performance as destabilization in pitch. Furthermore a dynamically unstable aircraft in pitch <u>and</u> yaw may multiply the complexity of the flight control system and hence is not very likely to pay off.

The consequence is that at low as well as at high angles-of-attack the design should aim towards coefficients and derivatives which produce at least indifferent roots in the dynamic analysis (slightly unstable spiral mode excluded).

The critical area for low angle-of-attack characteristics, control fixed, may be found at high supersonic Mach numbers. In the region of maximum dynamic pressure the elastic factors usually deminish the stabilizing contribution of the vertical tail. So the first criterion for the vertical tail size may be evaluated by fixing the desired root position of the dutch roll for the unaugmented aircraft, as shown in Fig. 19. A rough guess for the rigid and elastic aerodynamic data in this high dynamic pressure/low α case leads to the required fin volume.

For the low speed/high angle-of-attack region the sketches of Fig. 20 point out the desired basic characteristics in roll and yaw. Stable directional/lateral derivatives ($+C_{n\beta}$, $-C_{\ell\beta}$) with smooth behaviour versus sideslip, avoidance of yaw and roll departure tendencies, sufficient margin for spin resistance and effective rudder/roll control power especially at high incidences highlight the optimization goals.

The qualitative recommendations have to be defined more precisely by some numbers in order to start with detailed variation procedures in wind tunnel. This will usually be done by setting a minimum margin for the dynamic stability parameter $C_{n\beta dyn}$ and a required rudder power for roll coordination at high angles-of-attack.

4.1 $C_{n\beta dyn}$ – A Design Requirement at High Angles-of-Attack?

The dynamic directional stability parameter, $C_{n\beta dyn}$ has been developed to predict tendencies of directional divergence and spin tendencies at high angles-of-attack. It has been derived from the characteristic equation

$$A\lambda^4 + B\lambda^3 + C\lambda^2 + D\lambda + E = 0$$

using the experience that divergence usually occurs when the C-coefficient becomes negative. As shown in Ref. 1 many of the terms, contained in C are usually small enough to be neglected. The result of the evaluation leads to the conclusion that directional divergence is likely to occur, if

$$C_{n\beta dyn} = C_{n\beta} \cdot \cos\alpha - \left(\frac{i_z}{i_x}\right)^2 \cdot C_{\ell\beta} \cdot \sin\alpha$$

approaches zero or gets negative. This tendency was checked against the behaviour of several high performance aircraft and the correlation turned out to be fairly good.

So it has become common use for preliminary design to set a certain minimum positive margin for $C_{n\beta dyn}$ to make sure that spin tendency at high angles-of-attack is excluded.

The most important results of a detailed analysis of lateral/directional root location versus $C_{n\beta dyn}$ shown in Fig. 21 and 22 point out that it may not always be convenient to optimize for a high positive $C_{n\beta dyn}$. The roots presented in these plots have been calculated for a canard configuration at 28° angle-of-attack, near C_{Lmax}, Mach = 0.5, sea level. Dynamic derivatives gained from modified Datcom methods and dynamic wind tunnel testing have been used. A variation in $C_{\ell\beta}$ covers the $C_{n\beta dyn}$ range of ± 0.28. Fig. 21 shows that with a well damped roll of $C_{\ell p}$ = -0.5 the $C_{n\beta dyn}$ trend coincides with the expected movement of the roots. At $C_{n\beta dyn} \geq 0$ all the roots are located in the stable region of the complex plane. The same configuration with autorotation tendency ($C_{\ell p}$ = + 0.1) (Fig. 22) shows a more problematic behaviour: A complex pair of roots tend to move into the unstable half of the plane once the $C_{n\beta dyn}$ gets greater than zero. If in this case the chosen design $C_{n\beta dyn}$ is too positive the control system has to cope with an unstable high frequency mode near the ordinate which is very hard to stabilize.

The conclusion is, that the design aim 'positive $C_{n\beta dyn}$ at high incidences' which usually goes along with 'negative $C_{\ell\beta}$', has to be handled with care. At the same time it is necessary to seek for possibilities to keep the dynamic derivatives, especially the roll damping (stability axis), in stable areas.

4.2 Requirements for Yaw and Roll Control Power

The essential factors which influence the control power requirements in roll and yaw are listed in Fig. 23. Some of the design criteria for all moving fin, rudder, aileron, flaperon or thrust vector devices may be directly deducted from MIL-spec. as for example from requirements for 'Time to Bank', 'Engine failure during Take-off' and 'Take-off/Landing in Crosswind'.

Control power for stabilization or stability augmentation of the lateral/directional axis is dependent on the chosen basic stability characteristics, as discussed above. But as long as no excessive instability in roll or yaw has to be covered the control power deducted from the other criteria should be sufficient.

The capability to initiate and maintain coordinated rolls especially at high angles-of-attack represents a major point of interest especially for future fighter aircraft with high agility in this part of the flight envelope. Already during preliminary design phases these aspects may be covered. Fig. 24 illustrates within three sketches in the time domain the essential parameters which afterwards will lead to roll and yaw power, required from aerodynamic or thrust vector devices.

For preliminary design the roll performance of an aircraft may be sufficiently described by the Roll Time Constant T_R, the Maximum Roll Rate p_{MAX} and a 'Time to Bank to Ø degrees'. Especially at high angles-of-attack most of the control law designs try to avoid sideslip and therefore prefer a well coordinated roll around the velocity vector. So the 'pitch recovery margin' which has been provided according to the discussion in chapter 3.1 sets the first corner stone by defining the maximum achievable roll rate p_{VMAX} (roll rate around the velocity vector). A rough calculation shows that the roll power necessary to maintain this roll rate is far too small to get sufficient handling qualities: The resulting time constant T_R and as a consequence the 'Time to Bank' to an arbitrary bank angle is much too large for an agile aircraft. So once a requirement for 'Time to Bank' or a certain 'Roll Time Constant' is settled some additional roll acceleration, $\Delta\dot{p}_V(t)$ will be necessary during the first few seconds of the manoeuvre. In practice a 'Time to Bank' requirement leads straight towards a 'Time Constant' requirement if the maximum roll rate is fixed. Thus, to initiate a coordinated roll manoeuvre the necessary roll acceleration (around velocity vector) can be simply defined as:

$$\dot{p}_{VO} = \frac{p_{VMAX}}{T_{R\ REQ.}}$$

Fig. 25 now points out how the roll acceleration requirement has to be transferred into body fixed yaw and roll control power. For 'Zero Time' the required body fixed roll acceleration is given by

$$\dot{p}_O = \dot{p}_{VO} \cdot \cos\alpha \qquad (1)$$

and the body fixed yaw rate by

$$\dot{r}_O = \dot{p}_{VO} \cdot \sin\alpha \qquad (2)$$

The definition of angle-of-attack and calibrated airspeed/dynamic pressure, where the agility is required, leads to the deduction of the body fixed roll and yaw control power requirements. Some further analysis shows that for any coordinated roll manoeuvre onset the relation

$$C_{nO} = C_{\ell O} \cdot \frac{i_z^2}{i_x^2} \cdot tg\,\alpha \qquad (3)$$

must be satisfied.

The summary of all the discussions above is presented in Fig. 26 showing a 'design chart' for yaw and roll controllers at high angles-of-attack. The diagram (body fixed yawing moment versus body fixed rolling moment) contains the line of coordination (defined by equation 3) and the minimum requirements for C_n and C_ℓ (equation 1 and 2). The aileron and/or flaperons at high angles-of-attack usually produce an adverse yaw/roll characteristic as illustrated in Fig. 26. Starting from this characteristic it is now necessary to meet the coordination line above the requirement by providing the appropriate yaw control power. It gets evident that this does not only require a certain yawing moment C_n but also a C_n-C_ℓ characteristic of the yaw controller. Once the yaw/roll control behaviour is fixed by configuration details it is of no use to increase the yaw potential beyond the 'line of coordination'. The capabilities for a well coordinated roll manoeuvre will not improve.

5. CONSEQUENCES AND CONCLUSIONS FOR THE AERODYNAMIC DESIGN

Using the stability and control requirements, derived from chapter 3 and 4, the aerodynamicists together with overall design specialists, engine specialists etc. have to look for a well balanced compromise between subsonic and supersonic performance under the constraints discussed before.

Every aircraft design process starts with a 'Basic Configuration' which is used by all the people involved. It will be updated from time to time and finally be frozen. A first very important and very common effect within this process is, that if one subsystem is pushed to its technical limit this system becomes predominant in the whole design. A small further increase of demands on this subsystem will be followed by a large increase in costs, time and weight without getting essentially better performance. Therefore it is not advisable to design for the real technical limit because it will not pay off (Fig. 27).

In case of an unstable aircraft the 'Flight Control System' represents such a critical subsystem; so aerodynamic design should not drive the FCS to its technical limit. Performance of the aircraft does not change too much when for example wing planform is changed by a small amount; but the resulting pitch behaviour can have serious impact on the complexity of the flight control system which again will cost time and money.

The next question is, what principal wing planform and tail concept will be optimum for the aircraft. The answer depends strongly on the type of the aircraft, whether it shall be designed as a merely subsonic fighter, a subsonic/supersonic fighter or even as a 'supercruiser' which has its predominant performance and manoeuvre requirements in the high Mach number region (say Ma = 2.5 or 3). This question will not be discussed here. The only point which has to be mentioned is that a highly unstable fighter aircraft seems not to be feasible as a tailless delta configuration. Such a fighter demands more recovery moment than can be provided by a delta. So an aft-tail, a canard, or a pitch thrust vector nozzle is mandatory.

5.1 General Considerations about Aerodynamic Pitch behaviour

As discussed above the pitch behaviour is critical with respect to the combination of large design instability SM, no excessive pitch-up and sufficient pitch recovery in the whole angle-of-attack/Mach number range. It is possible to find the critical areas in plots C_m vs. α and Mach (Fig. 28). In the upper half such curves are shown for a 'normal' trapezoidal wing. Largest SM and $C_{m\alpha max}$ occur at low Mach number. Comparing this with Fig. 18 one can expect that a configuration with such a wing will be critical at some medium Mach number (say 0.5 to 0.7).

At transonic Mach numbers those planforms have less pitch-up or even pitch-down tendencies. The aerodynamic center has already moved aft relative to low Mach numbers so that instability should not be the problem any more. One rather has to pay attention, that possible pitch-down tendencies don't become too large, because this would have a negative influence on performance at higher α in that Mach number region, especially because of losses in maximum lift.

Other wing planforms as cranked wings fo example (wings with a kink in some mid wing station) can show a different behaviour (Fig. 28, bottom). At low α they have the normal a.c.-shift versus Mach number. At medium α the pitch-up tendency is extended up to even supersonic Mach numbers because of a transonic vortex burst at the kink station. Such a behaviour may become fatal for unstable aircraft, because the Time to Double 'T_2' may get below the margin which can be controlled by the FCS. This could be corrected by a flap schedule which is 'optimum' for FCS (less $C_{m\alpha}$) or by a reduction of basic instability margin. Both steps will finally penalize the design aims for good performance.

5.2 Choice of Wing Planform

The considerations made above lead to the conclusion that a trapezoidal wing possibly with a wing strake of a certain size, seems to be the best compromise for a fighter type aircraft.

Once the wing span and area is essentially fixed by the preliminary design which are mainly a result of subsonic/supersonic performance requirements and weight aspects, one still has the choice to select final values for the following parameters:

- Sweep/aspect ratio

  - a lower sweep will give:
    - less pitch-up tendency
    - smaller induced drag in the subsonic region which will result in a smaller span
  - a larger sweep will give:
    - more pitch-up
    - larger induced drag subsonically (larger span) but better supersonic performance relative to wing area (lower C_{Do}).

  A larger span can overrule the beneficial supersonic C_{Do} effects of higher sweep so that there will be an optimum depending on the requirements.

  Typical modern fighter wings have a leading-edge sweep of $\phi_o \approx 40°$ up to 55° and an aspect ratio from 2 to 3.

- Wing strake

  A wing strake (Fig. 29)

  - shifts aerodynamic center forward
  - increases C_{Lmax}
  - increases $C_{m\alpha max}$
  - decreases recovery moment

  A canard produces similar effects like a strake, but if it can be sufficiently deflected the recovery moment is not reduced.

The pitch characteristics of a trapezoidal wing including a strake can be plotted as a function of wing planform (Fig. 30). There exists a tendency of aspect ratio versus leading edge sweep for high lift configurations (with leading- and trailing-edge flaps down) which is similar to that of the so-called NACA pitch-up line. The solid curve in the figure shows the trend without strake. All wings on this line have the same pitch behaviour. This means that they produce for a given design instability of the configuration same pitch-up. If the planform is changed into the direction of high aspect ratio/high sweep the pitch-up increases. This is partly an effect of trailing-edge sweep: A more positive (aft swept) trailing edge sweep increases wing-tip stall at medium α and shifts the wing region concerned further aft of the center of gravity. Adding a strake (or a canard) pitch-up increases too and one has to select a lower aspect ratio/sweep combination to regain good pitch characteristics.

If the chosen configuration (for example with a given canard size) has a too large pitch-up, it is of no use to change the wing planform along the lines with same pitch-up characteristics, because the effect will be zero: One has to go more or less perpendicular to these lines.

5.3 Lateral Problems at High Angles-of-Attack

The $C_{\ell\beta}$ problem at high α can become a very nasty task to solve, because almost everything at the configuration can influence this important parameter often in a very unsystematical way. Main attention has to be drawn to all devices in front of the leading edge, i.e.

- leading-edge itself (LE drop, slats)
- forebody including cockpit
- strakes, canards, 'flow fixings'
- inlets
- external stores

and so on. From each of these devices vortices can emerge at high α which may affect the leading-edge vortices of a yawing aircraft in an asymmetric way. If the energy of the down wind leading-edge vortex is augmented by some other vortex, this energy is transported outboard towards the wing tip inducing a higher lift on the 'wrong' wing panel which results in a more unstable $C_{\ell\beta}$. Fig. 31 shows two examples of $C_{\ell\beta}$ behaviour in the critical α region: a stable one with a negative slope in C_ℓ versus β gives no problems. The other curve shows the typical behaviour of an unstable configuration. At large β the configuration is stable, but in a β range, say $\beta = \pm 10°$, (which is well within the flight envelope) it is unstable. When a configuration has such a behaviour and the project is already beyond the predesign phase one has the task to reduce the unstable $C_{\ell Cr}$ down to an acceptable stability by 'minor variations'. Experience shows that for small β it seems to be relatively easy to get stability with small changes. But an unstable $C_{\ell Cr}$ at larger β often seems to be relatively resistant to flow fixings and similar devices.

A canard (depending on its position) can aggravate the problem severely, especially when it is used as control device and hence movable. Then the vortex system is changed by every control deflection and a flow fixing optimised for one canard deflection needs not to be favourable for another.

Furthermore many of the measures to influence $C_{\ell\beta}$ affect other parameters like $C_{L max}$ and especially $C_{m\alpha}$ too. As pointed out in Fig. 32 there is a certain region in a pitch-up versus $C_{\ell Cr}$ diagram within which the possible effects of almost all 'small changes' applied to a basic configuration can be found. From such a diagram it is easy to select beneficial variations. With an increasing number of wind tunnel tests related to this problem, it becomes more and more difficult to find further beneficial variations whose effects are beyond the limit of this region. If one does not succeed in reaching the design target within a senseful time, one should change the basic configuration itself in order to shift its aerodynamic behaviour into the right direction.

This has to be off course a major variation like a change in wing planform/position or tail concept which deeply influences the whole design process.

6. CONCLUDING REMARKS

The discussions above about recommendations, requirements and limits which have to be taken into account in order to cover 'Flight mechanical' and 'Flight control system' points of view, have shown that it is mandatory to involve these aspects already into a preliminary design process of a modern fighter aircraft. The criteria which have been derived are of major influence for the overall configuration. In order to settle actual numbers which can be taken as corner stones for the aerodynamic design the following procedure can be recommended:

- Define the maximum allowable design instability in terms of $C_{m\alpha}$ versus Mach number. Start with the T_2-criterion at Ma = 0.9 and evaluate maximum allowable $C_{m\alpha} = f(Ma)$. Simple formulas for a first guess are given in Fig. 9 and 18.

- Define requirements for agility at high angles-of-attack, i.e. roll time constant T_R or 'Time to bank', maximum roll rate $p_{V max}$ in combination with calibrated airspeed and angle-of-attack.
  Evaluate the necessary recovery moment $\Delta C_{mRec.}$ according to Fig. 7.

- Define necessary fin volume at maximum Mach number/dynamic pressure by limiting the most unstable root location of dutch roll ($Re_{DR} \leq 0$), Fig. 19.

- Settle margin for basic lateral/directional stability at high angles-of-attack ($C_{n\beta dyn}$), Fig. 21 and 22.

- Evaluate necessary roll/yaw control power for coordinated roll manoeuvres at high angles-of-attack, Fig. 26.

- Check roll/yaw control power against conventional criteria according to summary in Fig. 23.

Maximum allowable instabilities and control power requirements, derived from above, will set remarkable constraints to the freedom of aerodynamic design and influence essential components of the aircraft. Because of the complex aerodynamic effects at high angles-of-attack it will be necessary to approach the 'basic configuration' by some optimization loops especially in low speed wind tunnel tests. During the whole process specialists from flight mechanics, aerodynamics and overall design departments have to form a close team in order to end up with an excellent well balanced design.

7. NOMENCLATURE

$\bar{c}$	[m]	aerodynamic chord	
CAP		control anticipation parameter	
C_D	[-]	drag coefficient	
C_{Di}	[-]	induced drag coefficient	
C_L	[-]	lift coefficient	
$C_{L\alpha}$	[rad⁻¹]	lift derivative	
C_ℓ	[-]	rolling moment coefficient	
$C_{\ell\beta}$	[rad⁻¹]	lateral stability derivative	
$C_{\ell p}$	[rad⁻¹]	roll damping derivative	
C_m	[-]	pitching moment coefficient	Body axis based on
$C_{m\alpha}$	[rad⁻¹]	pitching moment derivative	$\bar{c}$ or half span
$C_{m\delta}$	[rad⁻¹]	efficiency of pitch controller	
C_n	[-]	yawing moment coefficient	
$C_{n\beta}$	[rad⁻¹]	directional stability derivative	
$C_{n\beta dyn}$	[rad⁻¹]	dynamic lateral stability parameter $= C_{n\beta} \cdot \cos\alpha - (\frac{i_z}{i_x})^2 \cdot C_{\ell\beta} \cdot \sin\alpha$	
$C_{\ell pe}$	[rad⁻¹]	roll damping stability axis	
g	[m/s²]	acceleration due to gravity	
H	[m]	altitude	
i_x	[m]	radius of inertia in roll	
i_y	[m]	radius of inertia in pitch	body axis
i_z	[m]	radius of inertia in yaw	
Im	[rad/s]	ordinate of root locus plot	
Ma	[-]	Mach number	
m	[kg]	mass	
n	[g's]	load factor	
$\dot{n}$	[-]	load factor onset	
p	[°/s]	roll rate, body fixed	
p_V	[°/s]	roll rate, velocity vector	
$\dot{p}_V$	[°/s²]	roll acceleration, velocity vector	
$\dot{p}$	[°/s²]	roll acceleration, body fixed	
Q	[N/m²]	dynamic pressure	
q	[°/s]	turn rate	
R	[m]	turn radius	
Re	[rad/s]	abszissa of root locus plot	
r	[°/s]	yaw rate, body fixed	
$\dot{r}$	[°/s²]	yaw acceleration, body fixed	
S	[m²]	reference area	
SM	[%]	static margin $= -\partial C_m/\partial C_L$	
t	[s]	time	
T_2	[s]	time to double amplitude; controls fixed	
T_R	[s]	roll mode time constant	
T_t	[s]	time delay within flight control system	
T_V	[s]	time lag within flight control system	
V	[m/s]	airspeed	
$x_{a.c.}$	[m]	aerodynamic centre	
$x_{c.g.}$	[m]	centre of gravity	
α	[°]	angle-of-attack	
β	[°]	angle of sideslip	
$\ddot{\beta}$	[°/s²]	angular acceleration in sideslip	
η, δ	[°]	deflection of pitch controller	
$\dot{\eta}$, $\dot{\delta}$	[°/s]	deflection rate of pitch controller	
ρ	[kg/m³]	density	
Θ	[rad/s²]	pitch acceleration	
ω	[°/s]	turn rate	
ω_{osp}	[rad/s]	undamped frequency (short period)	
ω_{Dsp}	[rad/s]	damped frequency (short period)	
ζ	[-]	damping of short period	
ζ	[°]	rudder deflection	
Δ		increment of ...	
μ_L	[-]	$= 2\,m/(\rho S\bar{c})$	
ϕ	[°]	leading edge sweep	

Special indices:

St	steady state
EFF	effective
e	equivalent
Req	required
MAX	maximum
Str	strake
Cr	critical
Rec	recovery

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Summary of directional divergence characteristics of several high-performance aircraft configurations, NASA TN D-6993 (1972)

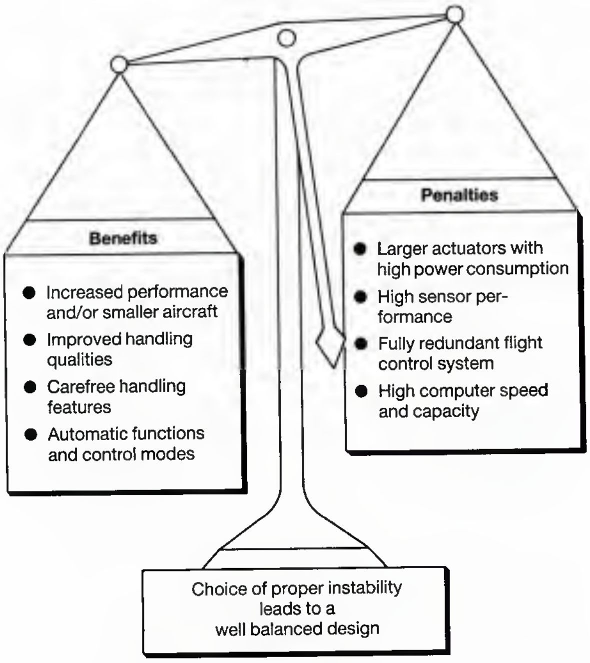


Fig. 1 **Benefits and Penalties of an (Unstable Designed) CCV-Fighter Aircraft**

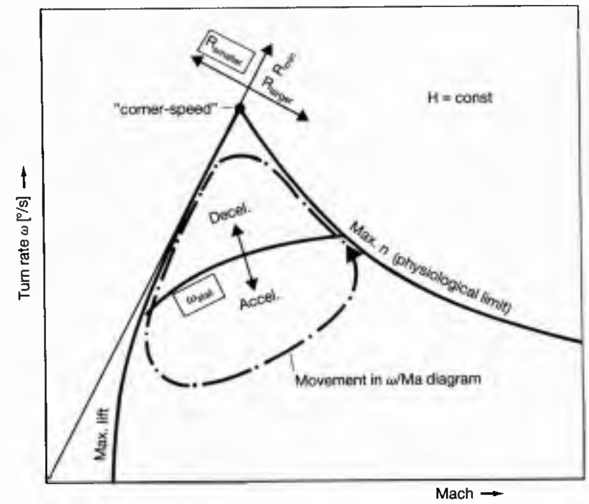


Fig. 2 **Development of a Dogfight (ω-Mach-Diagram)**

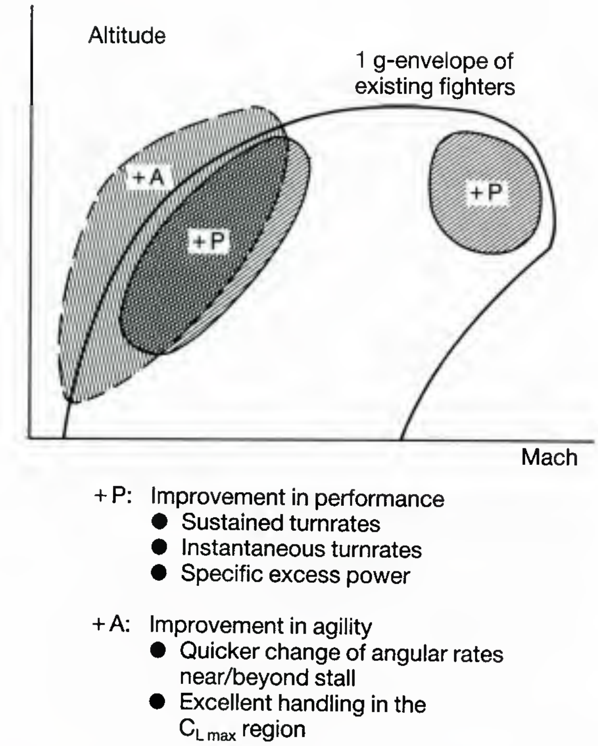


Fig. 3 **Areas within Flight Envelope of Major Interest for Improvement**

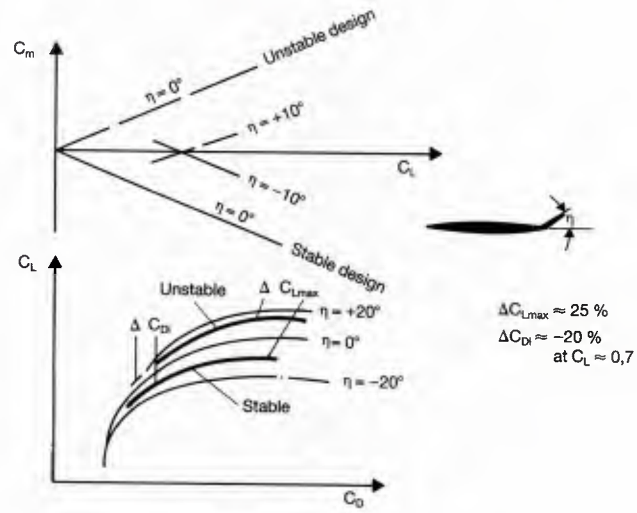


Fig.4 **Effect of Destabilisation on Performance**

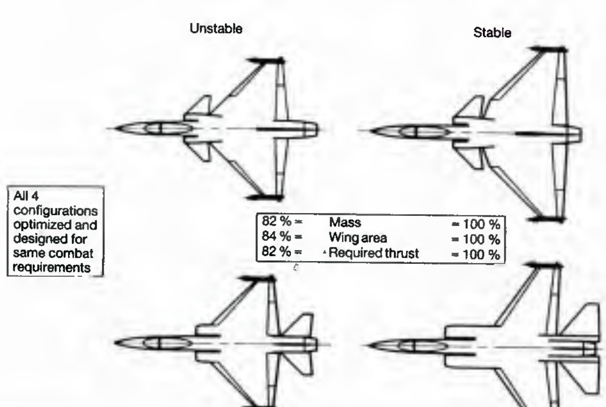


Fig. 5 **Effect of Optimum Unstable Design on Aircraft Size**

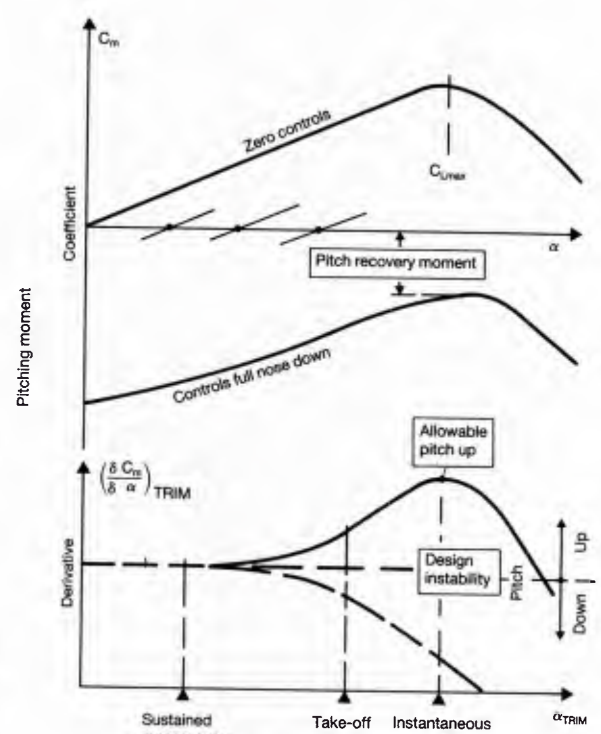


Fig. 6 **Problem Areas in Subsonic Pitch Characteristics of an Unstable Fighter Configuration**

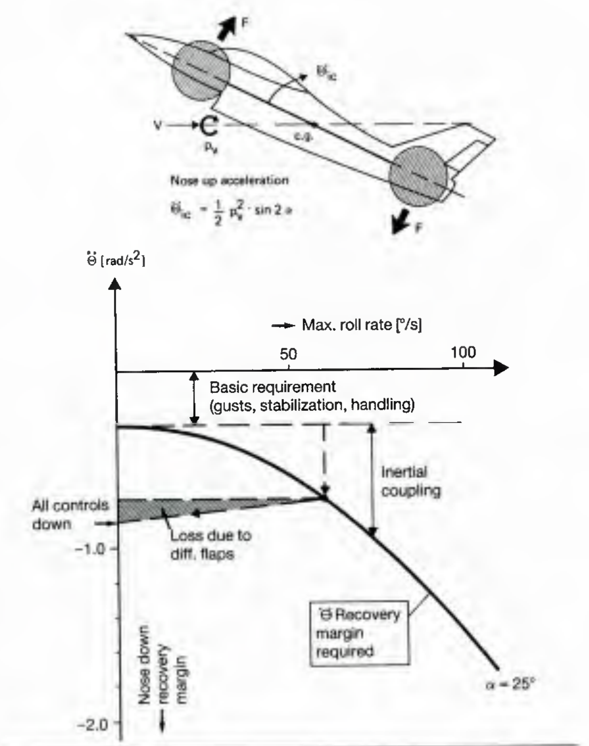


Fig. 7 **Definition of Pitch Recovery Margin at High Angles of Attack by Roll Rate Requirement**

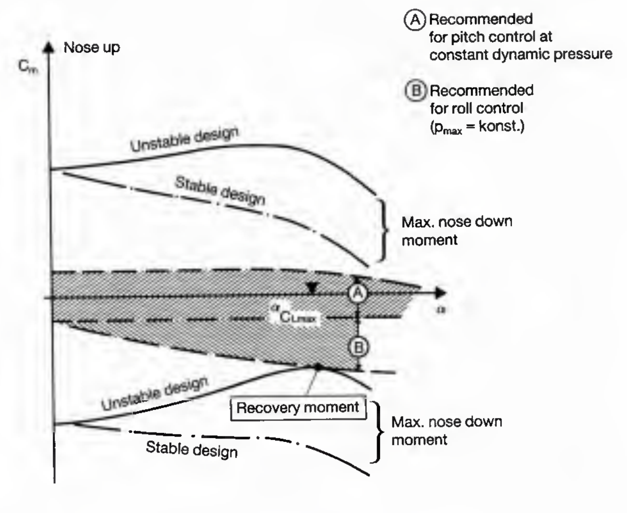


Fig.8 **Principals of Pitch Control Requirements**

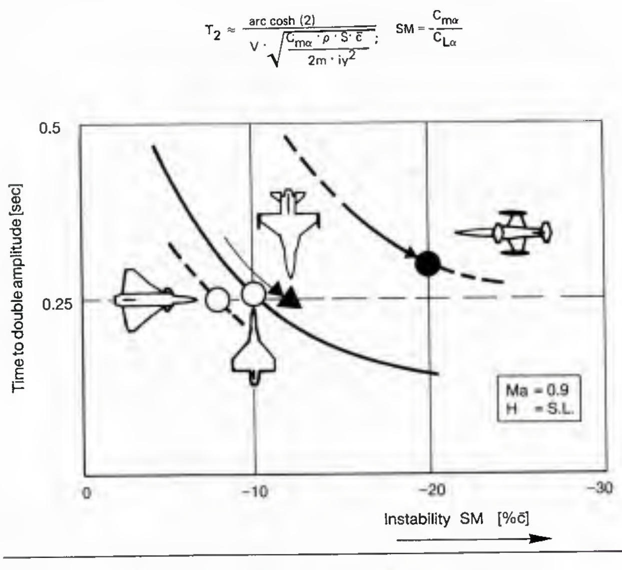
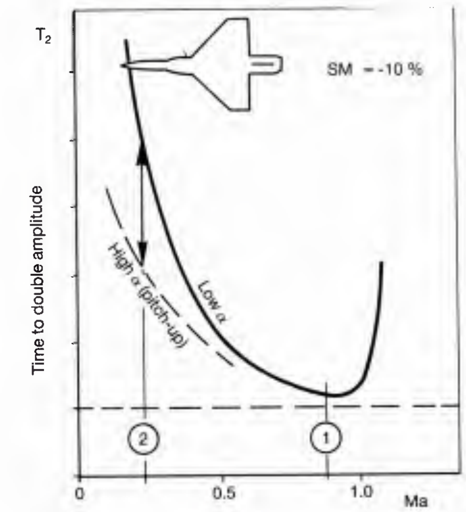


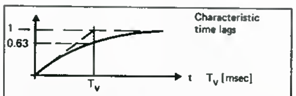
Fig. 9 **Estimated Time to Double Amplitude Versus Negative Static Margin of Some Existing and Projected Fighter Aircraft**



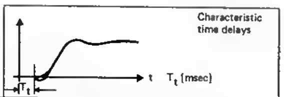
① Time delay budget within the control system sets limits to maximum design instability (T_2 not >> T_t)

② Control power in combination with pitch-up sets limits to maximum tolerable instability (Cm_α)

Fig.10 **Variation of "Time to Double Amplitude" Versus Mach-Number**



Angle of attack sensor with D/A-convertion	10
Rate gyro	5
Control of servo valves	5
Time lag of actuator and control device	40
Aerodynamic time lag (dependent on airspeed)	< 10?



Air data computation and filtering	10
Inertial skewed sensor computation and notch filters	15
Data transport	1
Computer transport delay	12
Voting and monitoring	10
Actuator time delay	1
Estimated Budget	40÷50

Fig. 11 **Estimation of Time Lag/Time Delay Budget within the Pitch Loops of the Flight Control System**

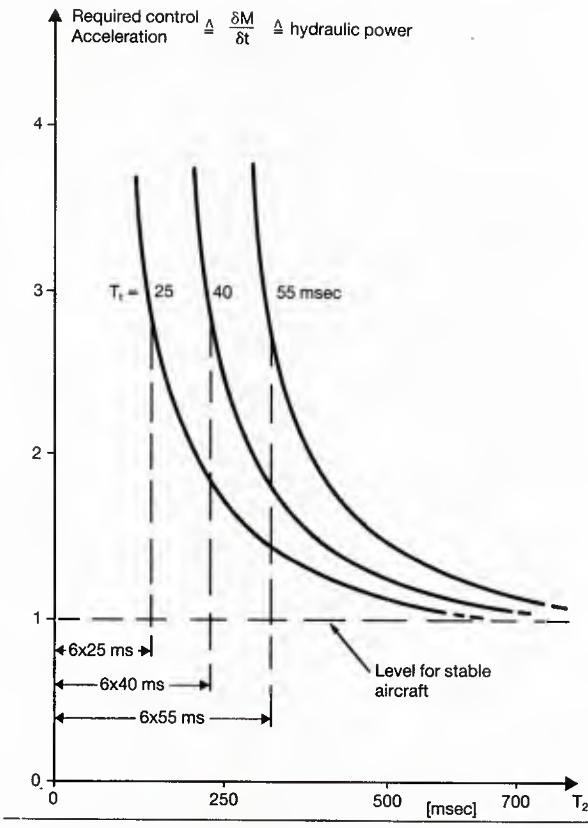
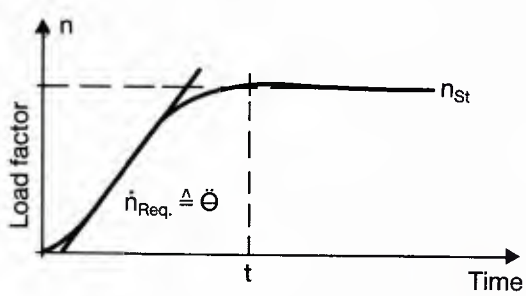


Fig.12 **Definition of Maximum Design Instability by Available Control Power Build-up**



Requirement: n_{St} to be reached after t sec.

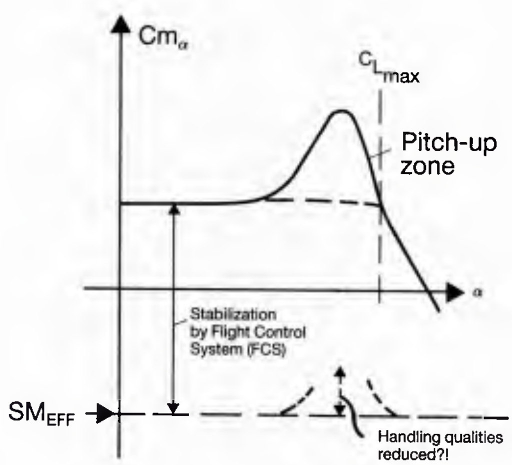
$$CAP = \frac{\ddot\theta}{\Delta n_{St}} \approx \frac{\omega_{osp}^2}{\frac{V}{g}\cdot\frac{1}{T_{\theta 2}}} \approx \frac{\omega_{osp}^2}{n/\alpha}$$

$$\frac{\omega_{osp}^2}{n/\alpha} \approx \frac{-\frac{Q\cdot S\cdot \bar c}{m\cdot i_y^2}\cdot C_{L\alpha}\cdot\left(\frac{C_{m\alpha}}{C_{L\alpha}}+\overbrace{\frac{C_{mq}}{\mu_L}}^{\text{Small}}\right)}{C_{L\alpha}\cdot Q\cdot S/(m\cdot g)}$$

$$\frac{\omega_{osp}^2}{n/\alpha} \approx -\frac{g\cdot\bar c}{i_y^2}\,\frac{C_{m\alpha}}{C_{L\alpha}} = \frac{g\cdot(X_{ac}-X_{cg})}{i_y^2}$$

- Handling qualities requirement "CAP" defines necessary effective "static margin" $SM_{EFF} = -C_{m\alpha}/C_{L\alpha}$

Fig.13
Evaluation of Basic Aerodynamic Characteristics from MIL Handling Qualities Requirements



- SM_{EFF} Required for optimum handling qualities
  (CAT. A, LEVEL 1*: CAP ≈ 0.9 ≙ SM_{EFF})
- Pitch-up compensation questionable:
  - Gain scheduling ⟷ sensor accuracy
  - Reduced control power (M, $\dot M$)

Fig. 14 **Principal Consequences of Local Pitch-up at High Angles of Attack**

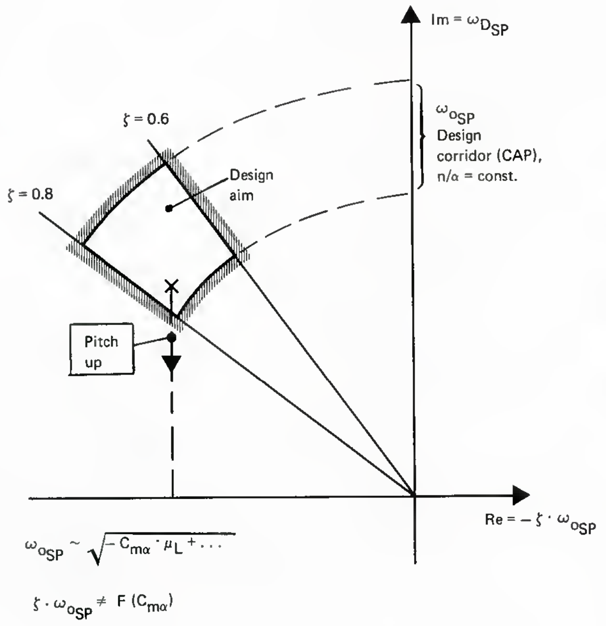
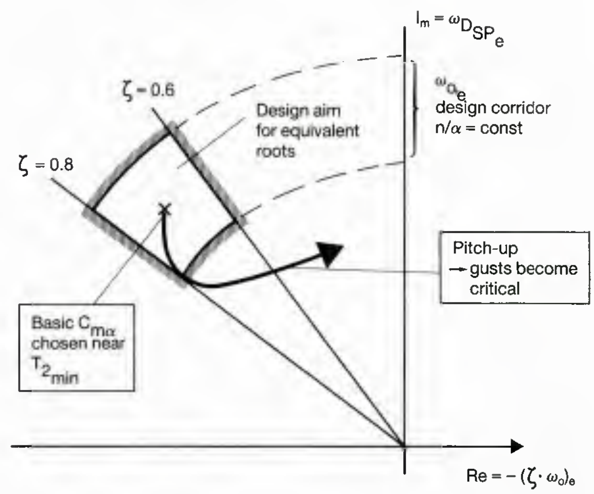


Fig.15 **Effect of "Pitch-Up" on Conventional, Stable (Non Augmented) Aircraft Root Location (Short Period)**



Low order system

Equivalent roots: Matching of $\dot{\Theta}$ and n_L transfer functions at point of rotation

High order roots: Actuator, sensors, command shaping, integration, . . .

Fig.16 **Effect of Pitch-Up on Equivalent Root Location of an Artificially Stabilized Aircraft (Equivalent Short Period)**

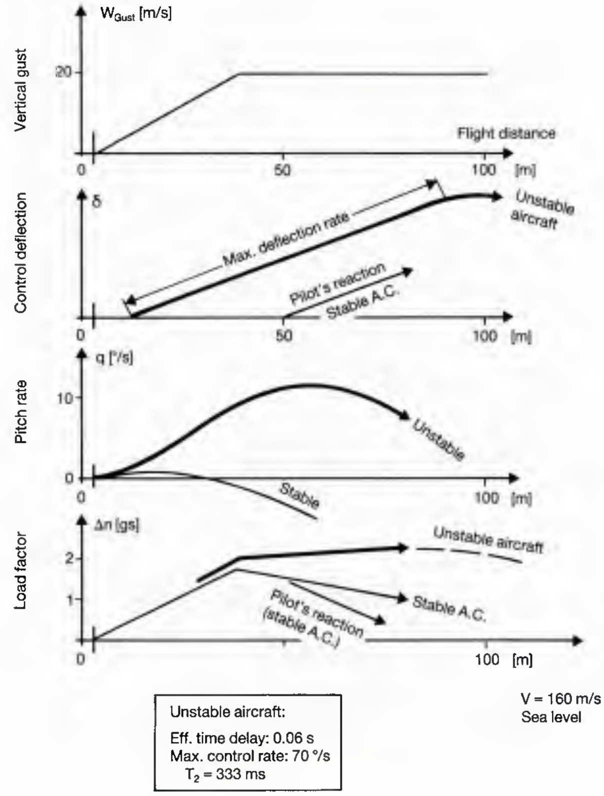


Fig.17 **Effect of too Large Instability (Pitch Up) on Gust Response (Sample Aircraft)**

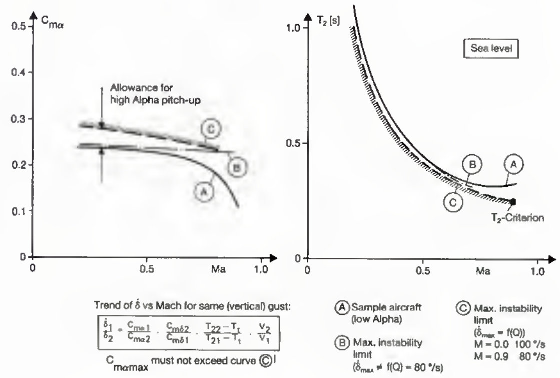


Fig.18 **Derivation of Instability Limits for a Sample Aircraft**

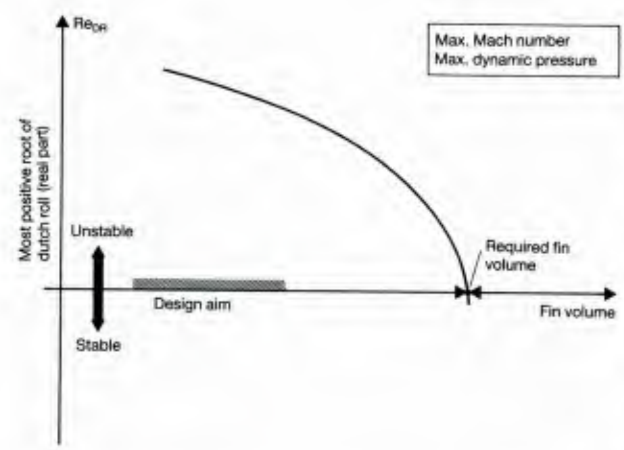


Fig.19 **Definition of Fin Size by Dynamic Characteristics at Low Alpha/High Dynamic Pressure**

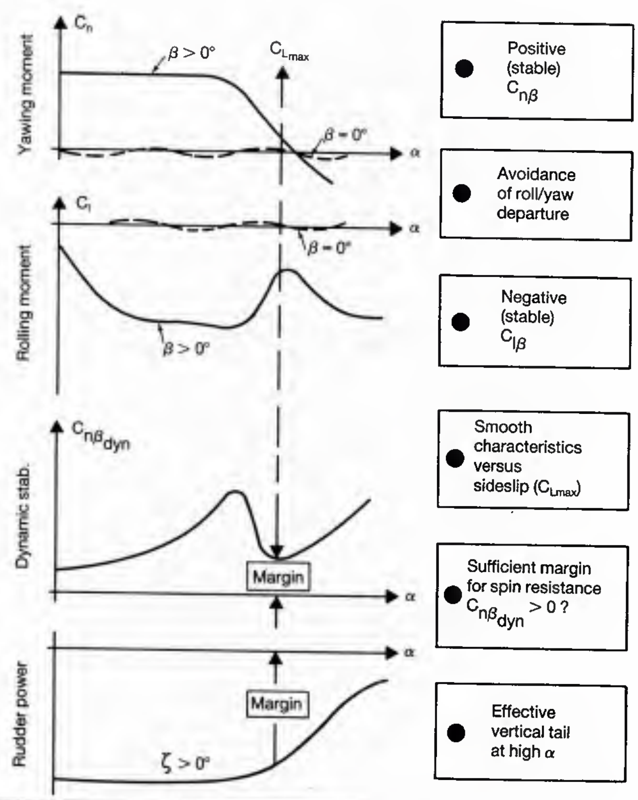


Fig. 20 **Design Requirements for Good Basic Lateral/Directional Characteristics**

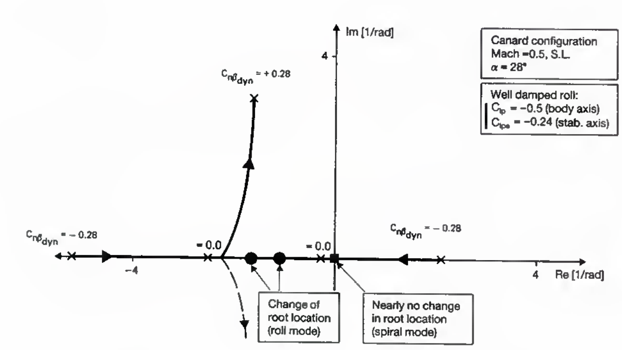


Fig. 21 **Correlation of Lateral Root Location with $C_{n\beta_{dyn}}$ at High Angles of Attack**

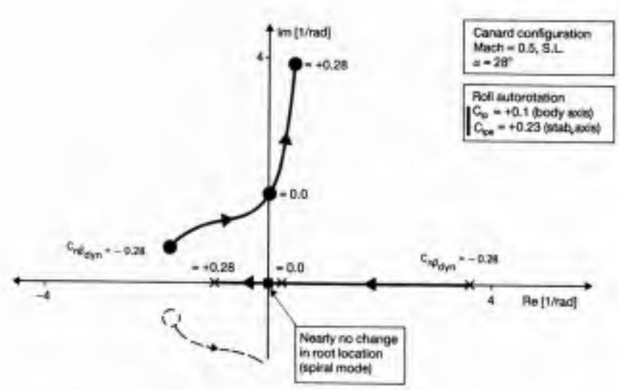


Fig 22 **Correlation of Lateral Root Location with $C_{n\beta_{dyn}}$ at High Angles of Attack**

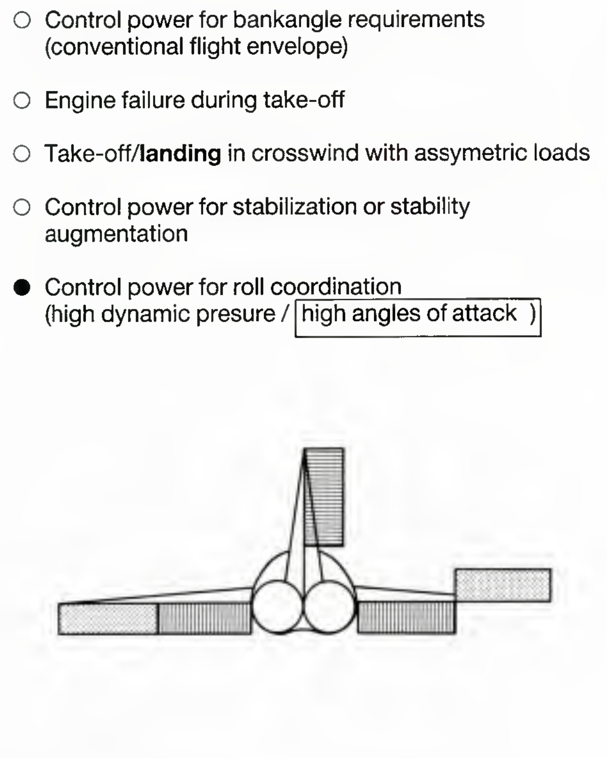


Fig. 23
Requirements for Yaw and Roll Control Power

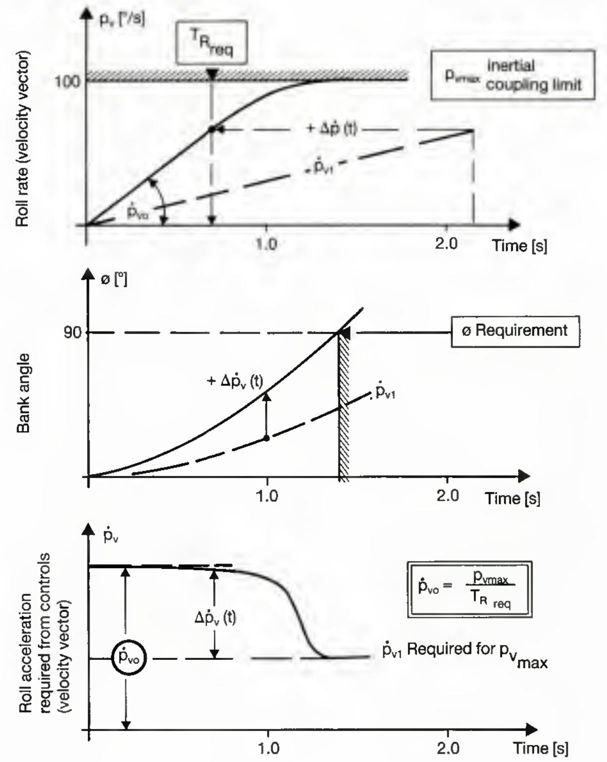
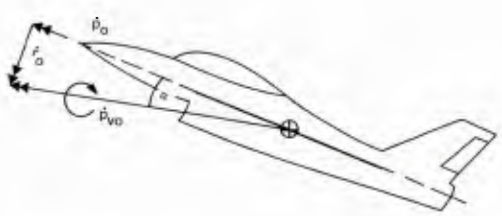


Fig.24 **Definition of Required Roll Control Power, $\dot{p}_{vo}$ (Velocity Vector), by "Bank Angle" – and "Rolltime Constant" – Requirements**



For Coordinated Roll Initialization Around Velocity Vector:

$$\dot{p}_{VO} = \dot{p}_o^{\,2} + \dot{r}_o^{\,2}$$

$\dot{p}_O = \dot{p}_{VO} \cdot \cos\alpha$ $\qquad$ $\dot{r}_O = \dot{p}_{VO} \cdot \sin\alpha$

C_{n_O}, C_{l_O} required at t = 0 sec

$$\boxed{C_{n_O} = C_{l_O} \cdot \frac{i_z^2}{i_x^2} \cdot tg\alpha}$$

Fig.25 **Deduction of Body Fixed Roll and Yaw Control Power for High Angle of Attack Roll Manoeuvres**

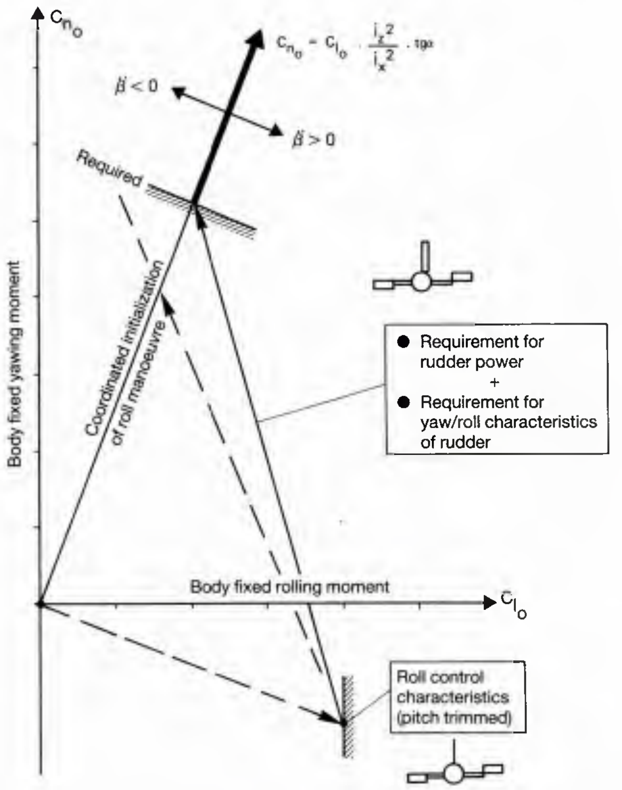


Fig. 26 **Design Chart for Roll/Yaw Controllers at High Angles of Attack**

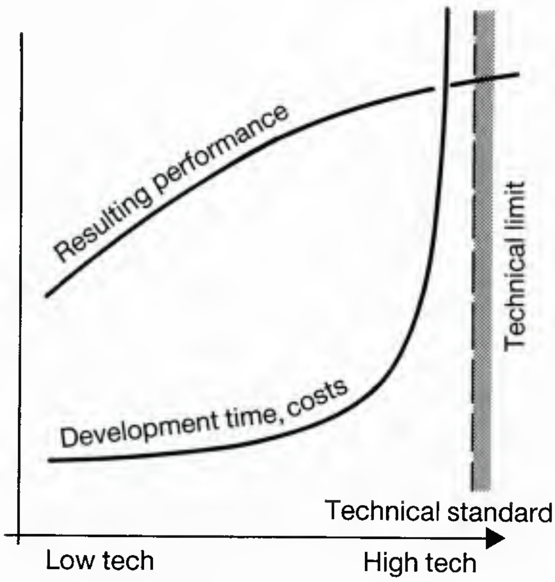


Fig. 27
Effect of Technical Standard on Performance, Development Time, and Costs

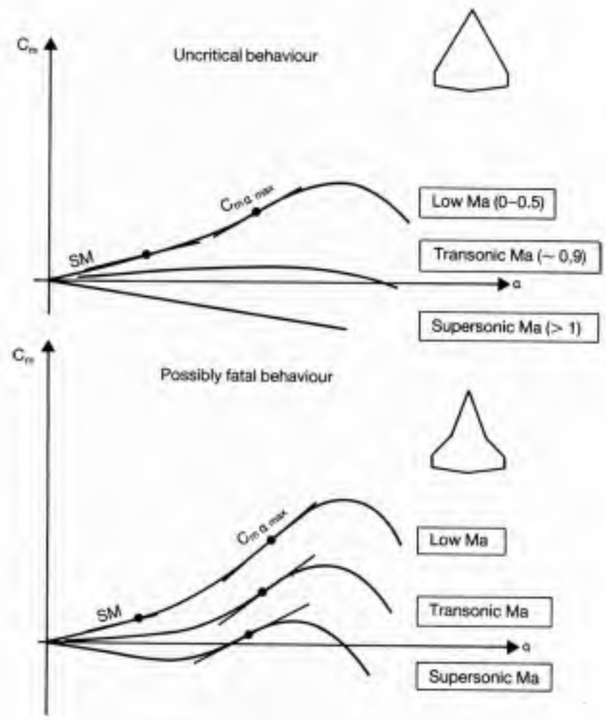


Fig. 28 **Pitch Behaviour of Unstable Aircraft (Zero Controls) for Different Mach-Number Ranges**

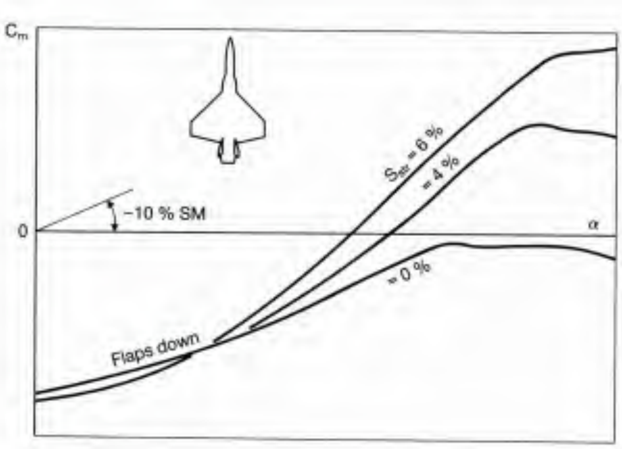


Fig.19 **Effect of Wing Strakes on Pitch Behaviour**

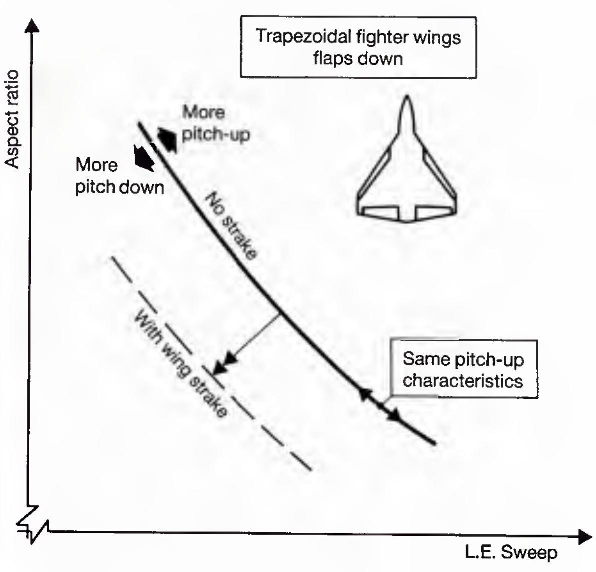


Fig.20 **Pitch-up Behaviour at Higher Angles of Attack as a Function of Wing Planform**

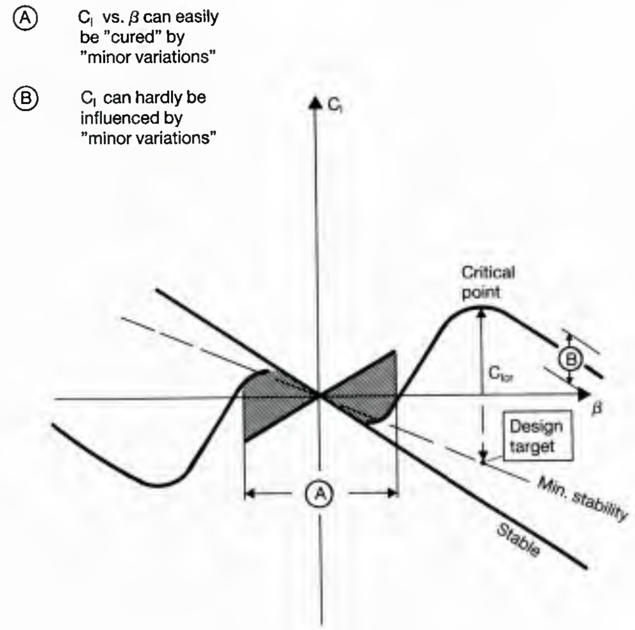


Fig. 31 **Typical Problem Areas in Lateral Stability Versus Sideslip at High Angles of Attack (Near Stall)**

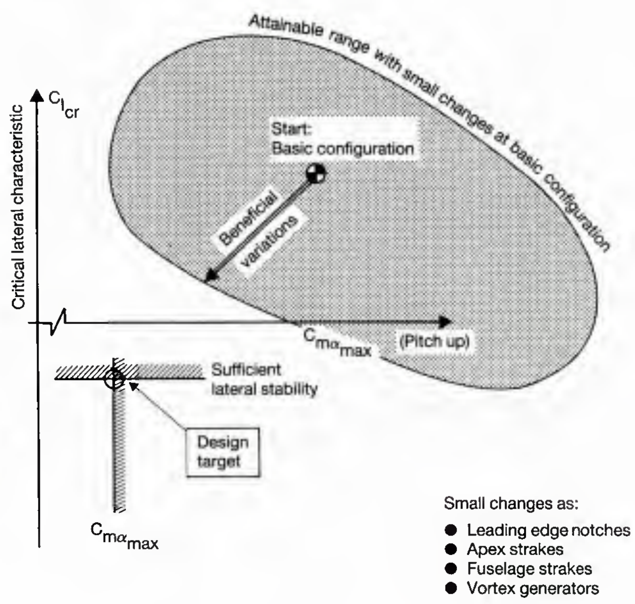


Fig. 32
Affectable Range in Combined Lateral/Pitch Behaviour for a Problematic Basic Configuration

SIMULATION AS A FIGHTER DESIGN TOOL

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SUMMARY

Simulation has been playing a growing role in the development of fighter aircraft weapon systems. In the 1960's and even early 70's simulation was almost exclusively the tool of the engineers responsible for the flight control and flying qualities of the airplane. However, in the last 10-15 years, simulation has seen ever increasing usage for tactics, crew workload and mission avionics assessment. This paper reviews the current status of real-time, pilot-in-the-loop flight simulation. It presents examples of simulators and a brief discussion of the components of a flight simulator with emphasis on the features of importance to the user. Fidelity as it relates to the perception of the pilot and his task performance is discussed. Data is given on the motion and visual requirements. The paper also presents key topics in experimental design including task selection, pilot factors and data collection. The paper concludes with an enumeration of technology improvements already on the horizon which are expected to make a major impact on simulation. Because of the extreme breadth of the subject matter, an extensive bibliography has been included.

1. INTRODUCTION

Simulation is a very broad term and even when restricted to fighter aircraft design, simulation is used in too many ways to be covered in one paper or lecture. For the purposes of this lecture therefore, treatment will be confined to non-linear, real time, pilot-in-the-loop air vehicle/weapon system simulation for research and development. The other major uses <u>not</u> treated here are (1) simulations (mostly non-real time) for engineering analysis; (2) air vehicle simulations for validation of avionics and flight control system hardware/software and; (3) simulations for operational pilot training.

Within this scope, the range of simulators and applications is still quite broad. Very simple fixed based simulators are often used for the development of controls and display concepts, in-flight simulators for ultra-realistic handling qualities validations, and elaborate multiple engagement ground facilities for exploration of technology/tactics interactions. In all cases the pilot/crewmember is the central element and the question that pervades all pilot-in-the-loop simulation is--does the simulation provide results which hold true in the real aircraft operational use? The keys to obtaining valid results are:

<u>Keys to Valid Results</u>

1. Know Your Simulator
2. Structure The Task
3. Value the Pilot

This lecture will therefore concentrate largely on these three elements. A recurring theme will be the "fidelity" of the simulation. A means to quantify overall fidelity has not been developed. As can be deduced from Figure 1, fidelity has many dimensions crewstation realism, vehicle model, visual scene, motion and sound, and in each dimension there are many parameters which influence fidelity. Since one-to-one engineering replication cannot be obtained, especially in the dimensions of visual and motion effects, the question becomes one of perceived fidelity.

The lecture is organized into the following five additional sections:

<u>Section 2</u>: Section 2 will discuss typical state-of-the-art simulators, both ground-based and in-flight.

<u>Section 3</u>: This Section will cover the typical configuration and usage of simulators for handling qualities, avionics, tactics, and flight test support.

<u>Section 4</u>: The visual, motion, and computational requirements for simulation will be covered in Section 4. Because of the close tie of requirements to human perception, this section will also include a brief treatment of human physiology.

<u>Section 5</u>: Section 5 covers key topics of experimental design including simulation validation, task selection, pilot considerations, and qualitative and quantitative data.

<u>Section 6</u>: The lecture concludes with the author's view of future trends in simulation.

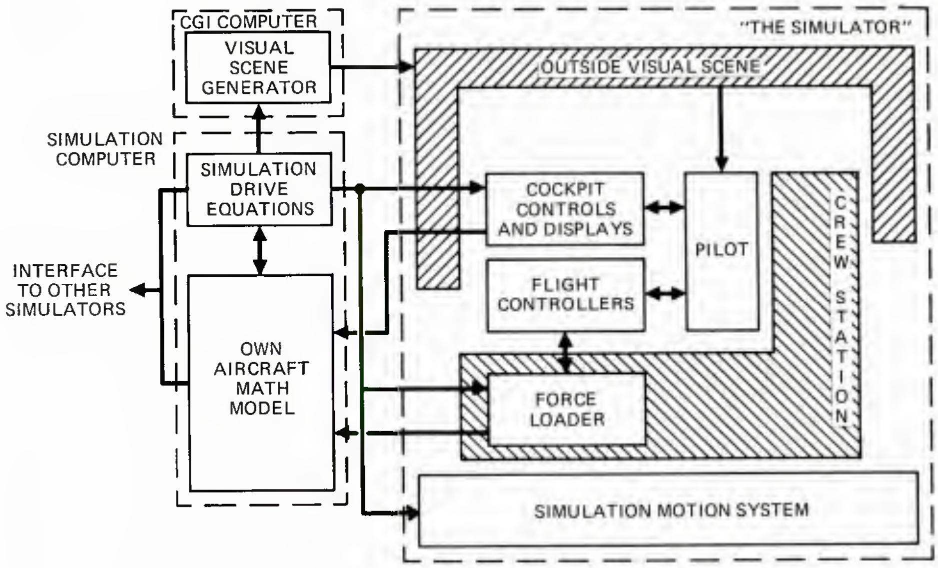

FIGURE 1. THE MAJOR ELEMENTS OF A FLIGHT SIMULATOR

2. SIMULATORS

Referring again to Figure 1, one can see the major elements of a simulator. Working outward from the pilot, the elements are the crewstation with its controls and displays and flight controllers. The purpose of the control force loader is to reproduce the force feel characteristics of the airplane such as aileron stick force gradient or rudder pedal gradients. If the simulator is a fixed mechanization of a given airplane, it will have a duplication of the aircraft feel system which is often times a system of springs. If, however, the simulator is intended for multiple users, then a computer programmable force loader system will be used. This may be electrohydraulic or electromechanical.

The crewstation is almost always provided with an "outside world" visual display. The visual display may range from a simple CRT setting where the windscreen would normally be, to a full 360° dome with projectors. This entire system can either be attached to the floor (fixed base simulator) or it can be placed upon a motion system providing flight motion cues (motion base simulator). This cockpit/visual/motion system sends commands to and accepts drive signals from a computer complex. The computer complex computes vehicle/weapon system states, does axis transformations, and computes cockpit motion, visual scenes and instrument readings. A more pictorial sketch of a typical flight simulator facility is shown in Figure 2.

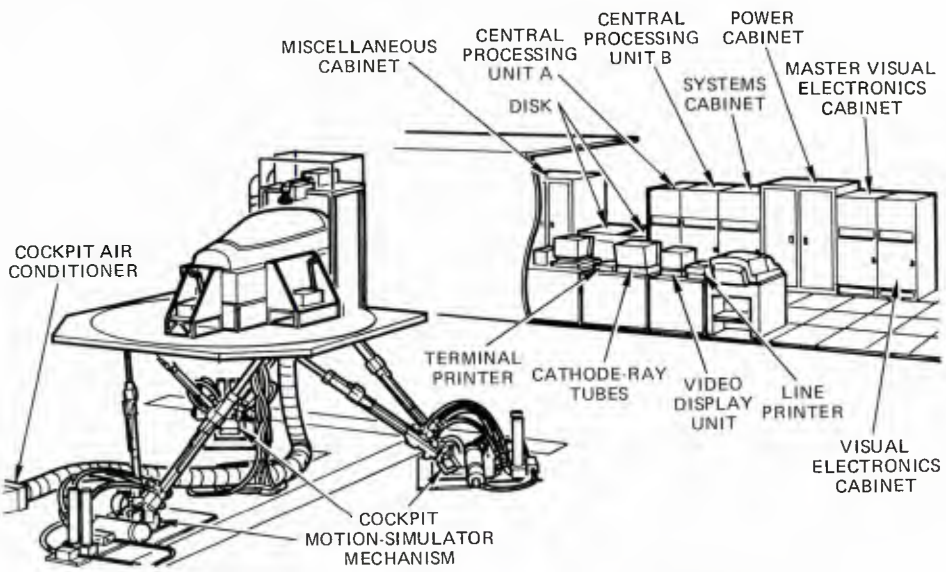

FIGURE 2. A TYPICAL SIMULATION FACILITY (MOTION BASE)

2.1 Fixed Base Simulator

Fixed base simulators can be very simple for the purpose of evaluating cockpit anthropometrics or display symbology or pagination. An example simulation crewstation of this type is shown in Figure 3. A more elaborate simulator is necessary for mission evaluation of the weapon system. In such an evaluation, one is concerned about dynamic system behavior, crewmember workload, and the resulting task performance. In this case, more elaborate "outside world" visual information is necessary. A typical simulator for this purpose is shown in Figure 4.

FIGURE 3. A TYPICAL CONTROL/DISPLAY DEVELOPMENT SIMULATOR

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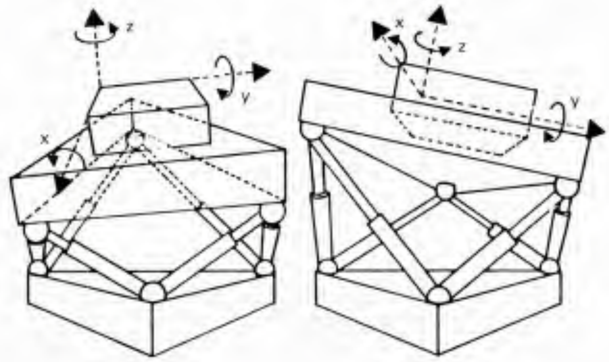
FIGURE 4. A TYPICAL AVIONIC WEAPON SYSTEM EVALUATION SIMULATOR

2.2 Motion Base Simulator

Motion base simulators are less numerous and are typically used for handling qualities evaluations. Motion systems consist of two major subsystems. First is the motion generation equipment. Second is the motion drive logic that computes the cockpit movements in response to computed aircraft motions. This motion drive logic is critical to the pilot's perception of flight and will be discussed in detail in Section 4.0. Motion generation can be achieved a number of ways, each with its pros and cons regarding performance.

Synergistic - Probably the most common motion system is the six-legged system shown in Figure 5. This system can produce limited motion in all six degrees of freedom. Synergistic systems are limited to small excursions.



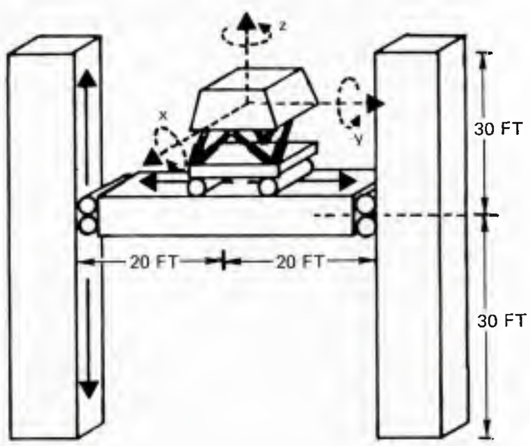
TYPICAL PERFORMANCE

KINEMATICS	VERTICAL	LATERAL	LONGITUDINAL	PITCH	ROLL	YAW
ACCELERATION*	+2G -1.9G	±0.7G	±0.9G	5.24 RAD/SEC^2	4.19 RAD/SEC^2	4.19 RAD/SEC^2
VELOCITY	+3.28 FT/SEC -2.46 FT/SEC	±2.95 FT/SEC	+2.95 FT/SEC -4.27 FT/SEC	+0.22 RAD/SEC -0.33 RAD/SEC	±0.28 RAD/SEC	±0.26 RAD/SEC
DISPLACEMENT	±4.5 FT	±5.25 FT	±6.07 FT	+34° -31°	±28°	±29°

* SUSTAINED FOR A VERY SHORT PERIOD

FIGURE 5. SYNERGISTIC MOTION SYSTEM

<u>Cascaded</u> - Cascaded motion systems build moving platforms upon moving platforms. A schematic diagram and typical performance of a cascade system are shown in Figure 6. A large cascade motion system is in place at NASA Ames in Moffet Field, California, but it is used primarily for V/STOL and helicopter development. A new simulator of this type called the AFS (Advanced Flight Simulator) was built for the Royal Aircraft Establishment (RAE) and has just recently become operational. It has performance more suitable for fighter aircraft development as shown in Figure 7. The main limitations of the cascade approach are cost and the performance of the outermost degree of freedom which must carry the weight of the nested inner motion platforms.



TYPICAL PERFORMANCE

KINEMATICS	X	Y	Z	PITCH	ROLL	YAW
ACCELERATION	16 FT/SEC^2	24 FT/SEC^2	32 FT/SEC^2	.87 RAD/SEC^2	.87 RAD/SEC^2	.87 RAD/SEC^2
VELOCITY	2 FT/SEC	10 FT/SEC	20 FT/SEC	.26 RAD/SEC	.26 RAD/SEC	.26 RAD/SEC
DISPLACEMENT	±2.5FT	±20 FT	±30 FT	±21.8°	±25.2°	±29.2°

FIGURE 6. CASCADE MOTION SYSTEM

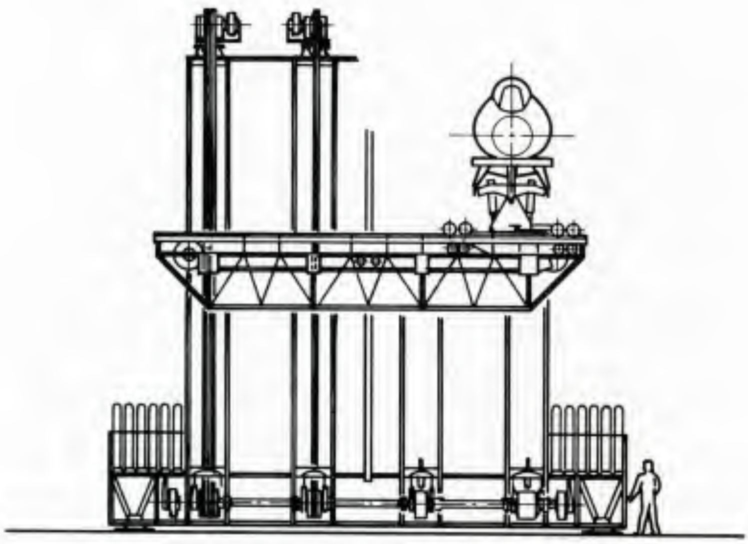
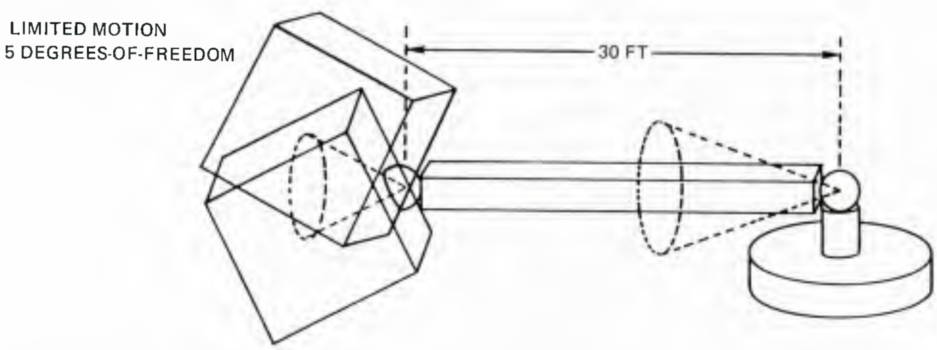


FIGURE 7. NEW RAE ADVANCED FLIGHT SIMULATOR – CASCADE MOTION SYSTEM

Beam - The beam motion system is characterized in Figure 8. The beam concept can produce 5-degrees of motion. The arm or beam can move up-down and left-right while the crewstation at the end of the beam is gimballed to move in roll, pitch, and yaw. The motion performance of this system is quite good. The Large Amplitude Motion Aerospace Research Simulator (LAMARS) simulator at the USAF Flight Dynamics Laboratory, Wright-Patterson AFB, Ohio, is a beam simulator and is shown in Figure 9



TYPICAL PERFORMANCE

KINEMATICS	VERTICAL	LATERAL	PITCH	ROLL	YAW
ACCELERATION*	±3G	±1.65G	7.0 RAD/SEC^2	8.0 RAD/SEC^2	3.5 RAD/SEC^2
VELOCITY	13 FT/SEC	10 FT/SEC	1.05 RAD/SEC	1.05 RAD/SEC	.87 RAD/SEC
DISPLACEMENT	±10 FT	±10 FT	±25^o	±25^o	±25^o

* SUSTAINED FOR VERY SHORT PERIODS

FIGURE 8. BEAM MOTION SYSTEM

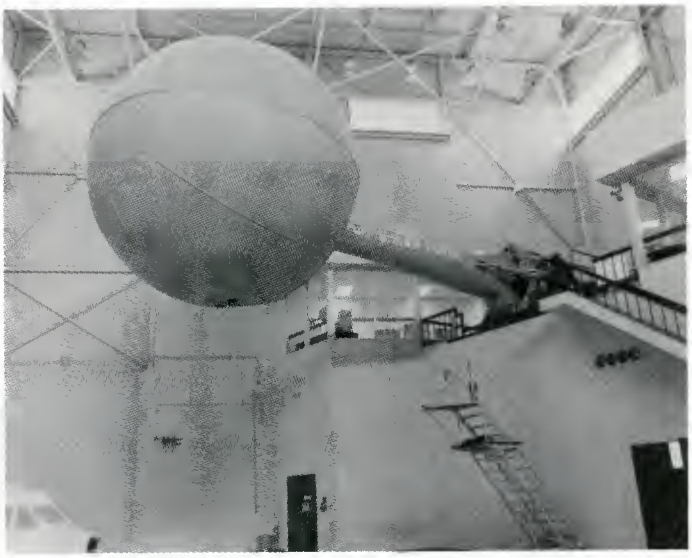


FIGURE 9. USAF FLIGHT DYNAMICS LABORATORY LAMARS

Suspended - This motion concept is very much like an upside-down synergistic system. The cockpit swings on arms from an overhead platform. A schematic of a typical suspended system is shown in Figure 10.

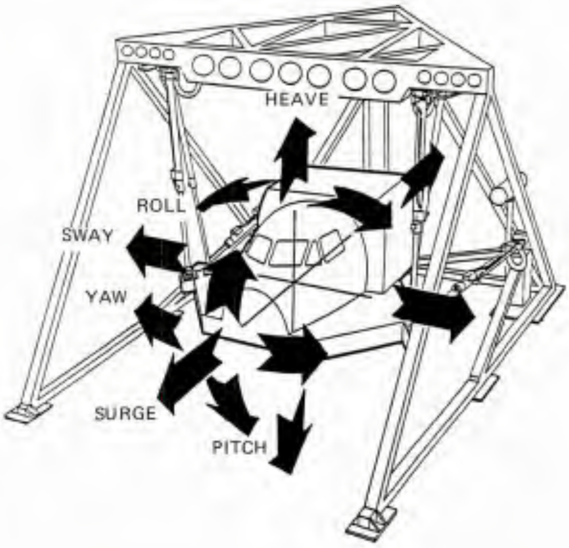


FIGURE 10. SUSPENDED MOTION SYSTEM

Visual System - The generation of a good outside world visual scene is critical to most simulation usage. Much development effort has historically been spent in pursuit of a good cost effective approach. Figure 11 shows the variety of approaches that can be taken. Until about 1975 the most popular approach was to use a physical model, more commonly called a "terrain board" captured by a television camera probe and projected on a screen. Today the most popular approach is to use a computer-stored data base and to project a computer generated image (CGI) either onto a screen or through infinity optics. A visual system is only as good as its weakest link. The complicated series of steps from storage to display has led to many unacceptable visual systems in the past.

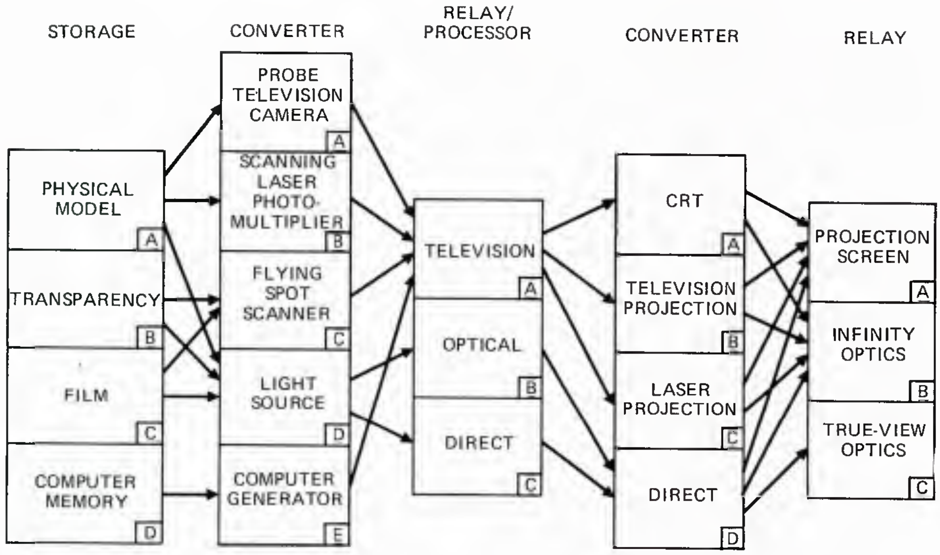
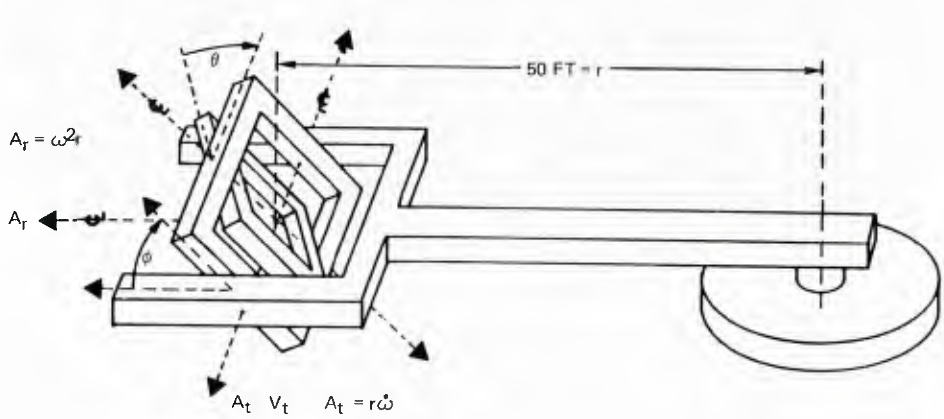


FIGURE 11. TYPICAL VISUAL SYSTEM COMPONENTS AND COMBINATIONS

2.3 The Centrifuge

The centrifuge will be given only limited treatment here because it is rarely used for pilot-in-the-loop simulation and they are not among the standard repertoire of simulation tools used in the design of a new fighter aircraft.

A typical centrifuge motion system is shown in Figure 12. Some of the more notable uses of the centrifuge for fighter aircraft design have been to determine the effect of seat back angle on g-tolerance and more recently to understand the effect of the rate of change of g on pilots. The DFS (Dynamic Flight Simulator - Ref. 22) centrifuge at the Naval Air Development Center in Warminster, PA, has a max sustained g capability of 40g's (man rated to 15g's) and can vary g's at up to 9 g's/sec. This ability to sustain and control all three components of the linear g-vector is a feature missing in all the other motion systems described above. Because of this feature, attempts have been made to place a simulation cockpit in the centrifuge gondola and conduct pilot-in-the-loop simulations. Reference 23 describes an F-14 stall-spin study. These early attempts were relatively unsuccessful due to the unwanted pitch and roll angular motions associated with varying the magnitude of the g-vector. More recent research described in Reference 21. has developed new gimbal drive algorithms which better account for the pilot's angular thresholds of perception. There are therefore new hopes that useful pilot-in-the-loop results can be obtained from the centrifuge for those tasks where sustained load factor is critical.



TYPICAL PERFORMANCE

KINEMATICS	RADIAL	TANGENTIAL	ARM	ROLL (φ)	PITCH (θ)
ACCELERATION	15G (MANRATED) 40G MAX	90.09 FT/SEC^2	1.8 RAD/SEC^2	6.5 RAD/SEC^2	9.5 RAD/SEC^2
VELOCITY	–	254 FT/SEC	5.08 RAD/SEC	3.14 RAD/SEC	3.14 RAD/SEC

FIGURE 12. CENTRIFUGE MOTION SYSTEM

2.4 In-Flight Simulation

An in-flight simulator is a real flying aircraft with an onboard computerized flight control system (usually called a variable stability system) which can make that aircraft respond to pilot inputs like the simulated aircraft. In-flight simulators are usually at least two place aircraft so that a safety pilot can monitor the experiment and take control at any time reverting to the original aircraft's flight control system. The evaluation pilot is in the "simulation cockpit" and can fly the aircraft through the special variable stability system (VSS). In the simulation mode, the aircraft, cockpit instruments and controller force feel system are driven by the VSS. The VSS has been programmed to make the aircraft respond and feel to the evaluator like the simulated aircraft.

The VSS can be either a response feedback system or an explicit model following system. The response feedback concept is similar to a conventional flight control augmentation system except that the gains in the control laws are brought to a control panel and are under experimental control. By properly setting these gains, the response dynamics of the in-flight simulator aircraft can be made to match those of the desired aircraft. Response feedback VSS systems often require several calibration flights to establish the exact gain settings for a proper simulation. Model following systems require a full equations of motion computation of the simulated aircraft on-board the in-flight simulator. The evaluation pilot's control commands go into the on-board simulation computer which computes the output states of the simulated aircraft to those commands. The in-flight simulator then is forced to follow those output states through a combination of feedforward and feedback loops in the VSS. The model following VSS is more costly and results in a more complex onboard mechanization. However, once the feed-forward and regulator gains are established for tight model following a new simulation can be validated with a minimum of flight time. Most of the simulation checkout can be done on the ground by testing the onboard model.

A typical in-flight simulator is the NT-33A shown in Figure 13. This is a USAF research vehicle managed by the Flight Dynamics Laboratory at Wright Patterson AFB and flown by Calspan out of Buffalo, N.Y. It has a response feedback VSS. This aircraft was first conceived in about 1954 to conduct in-flight simulations of the X-15 flight characteristics. It has more recently been used in the development of a whole series of fighters including the A-9, A-10, F-15, YF-17, F-16 and F-18 (See Reference 7).

FIGURE 13. USAF NT-33A IN-FLIGHT SIMULATOR

Other examples of slightly larger in-flight simulators include the USAF/Calspan TIFS (Total In-Flight Simulator) the MBB HFB 320 executive jet, the DFVLR VFW-614 ATTAS (Advanced Technology Testing Aircraft System), and the Calspan Lear Jet. These aircraft are mentioned because, in spite of their non-fighter classification, they are able to simulate some tasks and response dynamics typical of a fighter class aircraft. For example, the TIFS was used to simulate the low speed characteristics of the forward swept wing X-29 prior to its first flight. A list of in-flight simulators in use in North America and Europe is shown in Figure 14, derived from Reference 29.

COUNTRY	AIRCRAFT (TYPE AND APPR. MASS)	MANUFACTURER	SPEED RANGE (KTS)	DEGREES OF FREEDOM	REMARKS
USA	NT-33A (FIGHTER AIRCRAFT; 5400 KG)	LOCKHEED	120-375	3 (ROTATIONS, FULL AUTHORITY WITHIN HINGE MOMENTS)	USED BY GD PRIOR TO YF-16 FIRST FLIGHT (SIDE STICK FORCE CONTROLLER); ALSO IN USE BY BOTH TEST PILOT SCHOOLS FOR INSTRUCTION AND TRAINING; OPERATOR: CALSPAN
USA	X-22A (4-ENGINED V/VSTOL (RESEARCH) AIRCRAFT WITH 4 DUCTED PROPELLERS; 8000 KG)	BELL	-30-150	4 (FULL AUTHORITY WITHIN HINGE MOMENTS; THRUST)	T/W=1.35, USED FOR WELL OVER TEN YEARS EXTENSIVELY IN SEVERAL PROGRAMS (TAKE-OFF, LANDING AND TRANSITION); NOW PROBABLY NEAR END OF SERVICE LIFE; OPERATOR: CALSPAN
USA	LEARJET (GENERAL AVIATION AIRCRAFT; 6000 KG)	GATES LEARJET CORPORATION	100-325	3 (FULL AUTHORITY WITHIN HINGE MOMENTS)	AIRCRAFT WILL TAKE OVER THE ROLE OF THE B-26 AS A TRAINING TOOL FOR THE TEST PILOT TRAINING SCHOOLS; OPERATOR: CALSPAN
UK	JAGUAR T2 (FIGHTER TRAINER AIRCRAFT)	BRITISH AEROSPACE	120-300	4 (FULL AUTHORITY WITHIN HINGE MOMENTS; THRUST)	DIGITAL FLY-BY-WIRE RESEARCH AIRCRAFT – MAIN EMPHASIS ON FLYING QUALITIES, ACT, STABILITY MARGIN, SYSTEM ARCHITECTURE, ETC.; OPERATOR: BAE
UK	HARRIER T2 (TWO SEAT VSTOL FIGHTER AIRCRAFT)	BRITISH AEROSPACE	-30-500	5 (LIMITED AUTHORITY AT PRESENT, FULL AUTHORITY IN FUTURE)	VSTOL/STOVL RESEARCH AIRCRAFT – MAIN EMPHASIS IN ON ADVANCED CONTROL AND DISPLAYS FOR THIS CLASS OF AIRCRAFT; OPERATOR: RAE

N.B. THE UK RESEARCH AIRCRAFT (JAGUAR AND TWO SEAT HARRIER) IN THE ABOVE LIST ARE NOT CONSIDERED AS GENERAL PURPOSE IN-FLIGHT SIMULATORS, BUT RATHER AS VERSATILE AND COMPLEMENTARY TOOLS TO THE AVAILABLE GROUND BASED SIMULATORS. IN THE CONTEXT OF THE HARRIER AIRCRAFT THE TAV-8A AND YAV-8B CAN BE MENTIONED. THESE AIRCRAFT COULD HAVE SUBSTANTIAL IN-FLIGHT SIMULATOR CAPABILITY, ALTHOUGH BOTH HAVE THEIR LIMITATIONS.

FIGURE 14. LIST OF AIRBORNE FLIGHT SIMULATORS IN NORTH AMERICA AND EUROPE

2.5 Remotely Augmented Vehicle

The NASA Ames Dryden Flight Facility has experimented with in-flight simulation by means of data links to and from the VSS computer on the ground. This concept is called a Remotely Augmented Vehicle or RAV (See Figure 15). The experimental aircraft, in this case the Digital FBW F-8, is equipped with an onboard encoder and decoder and the ability to have its FBW system commanded by the onboard control laws or by the up-link. In the RAV mode the pilot's commands and motion sensor measurements are encoded and sent on the down link to the ground computer. The control laws in the ground computer output surface commands which are transmitted on the uplink to the F-8. Just like the conventional response feedback VSS the gains in the ground control laws can be selected to achieve the desired response characteristics. In the RAV concept a successful simulation must be especially careful of loop time delays. The telemetry transmission time is not a problem. For a typical operating range from base of 20 miles, the round trip time delay is on the order of 0.2 msec. However, one must be aware of the overall delays including encoding/decoding update rates as well as the ground computer computational delays. A more detailed discussion of the effect of time dealys can be found in section 4.6.

The RAV concept is in very limited use today largely because of the unique combination of range, telemetry, and ground simulation facilities to conduct such a simulation.

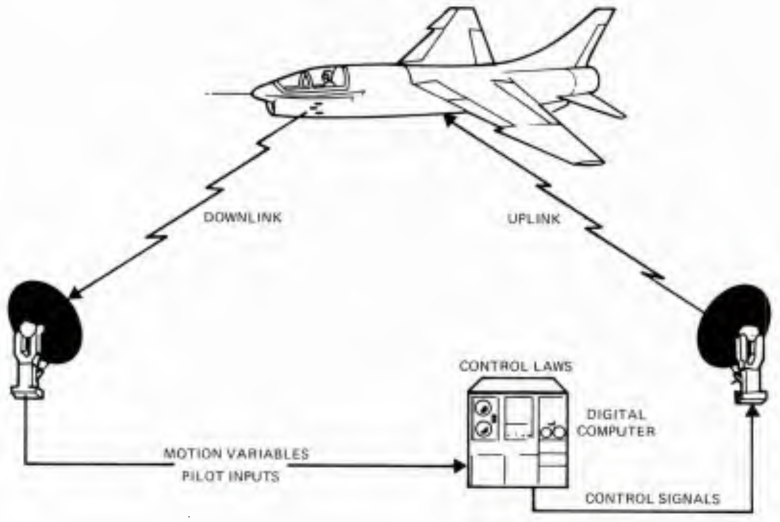


FIGURE 15. REMOTELY AUGMENTED VEHICLE CONCEPT

3. TYPICAL USAGE

Pilot-in-the-loop simulation is used throughout the life of a new development program. As shown in Figure 16 the objective of the simulations change with time as the program evolves.

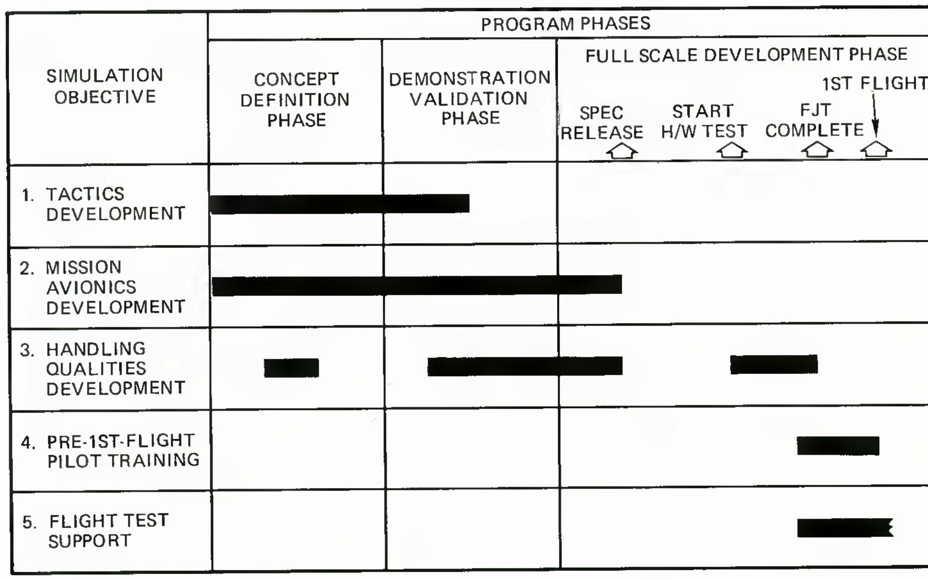


FIGURE 16. TYPICAL SIMULATOR SCHEDULE VS FIGHTER DESIGN SCHEDULE

3.1 Tactics Development

In the earliest stage of a new aircraft development fundamental questions of aircraft sizing and technology payoff are being addressed. An assessment of the vehicle and weapon system performance in a realistic tactical/threat environment is required to guide the concept definition. Todays fighter aircraft designs are dominated by four facts of modern air warfare; the importance of (1) control of the electromagnetic environment, (2) command and control, (3) beyond visual range (BVR) missiles, and (4) many-on-many engagements. There are some limited analytical tools available such as TACBRAWLER for tactical battlefield assessment; however, their utility is limited. One finds in simulation, as in actual in-flight combat training, that pilots are extremely resourceful and inventive. The insertion of new technologies into the problem may result in the development of a new set of operational tactics. The effect of such creations are of course not codified in existing analysis tools.

The ability to conduct M-on-N air combat engagements in the BVR environments including the effects of threats, ground/airborne controlled intercepts, and jamming and countermeasures is described in Reference 20. A typical M vs. N simulator system is shown in Figure 17 which shows a red force of 8 on a blue force of 4 with each side having ground controlled intercept (GCI). In this case, the BVR stations are as shown in Figure 18. Each BVR station has a CRT display as shown in Figure 19. Domed simulators are also shown tied into the system. When the adversaries and friendlies are within visual range, they can be displayed on the dome interior as shown in Figure 20.

A key element in the creative use of such a tool is the pilot subject. Operational experience is critical in the discovery of the optimum tactics/technology complement to win the airbattle.

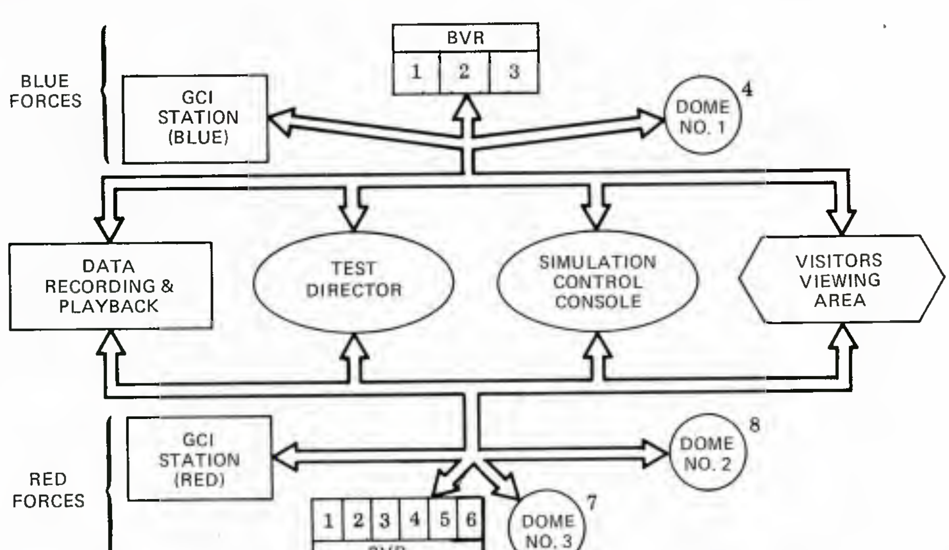


FIGURE 17. MULTIPLE ELEMENT ENGAGEMENT SIMULATION

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FIGURE 18. INTERACTIVE CONTROL STATIONS

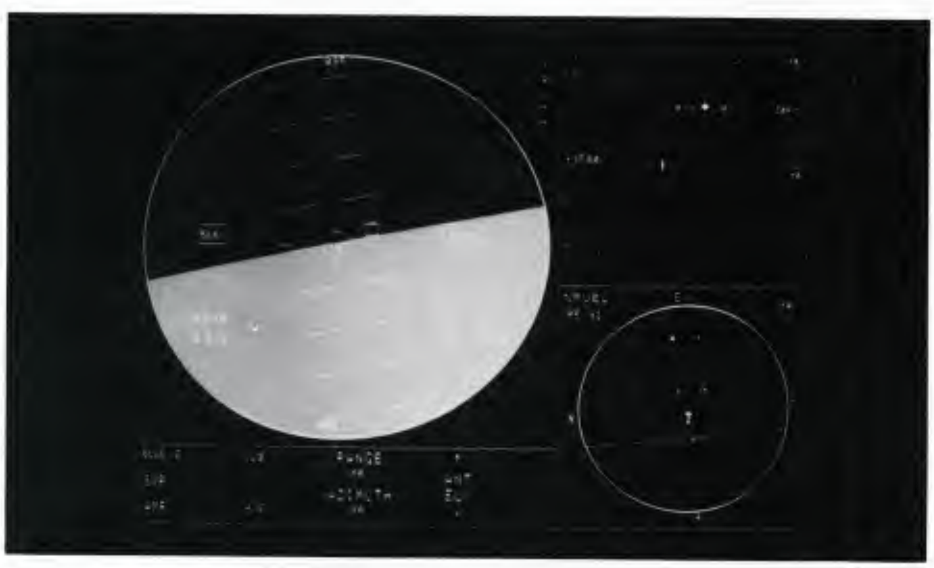

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FIGURE 19. BVR GRAPHICS CONSOLE

FIGURE 20. MULTIPLE AIRCRAFT DISPLAYED ON DOME

3.2 Mission Avionics Development

At a somewhat more detailed level of development, one must insure that the crewstation, weapons systems, and integrated controls are designed from a pilot centered point of view. The critical question here is one of "workload;" that is, do the weapons system controls and displays possess the proper degree of automation and do the moding and display pagination and symbology support the required mission timelines. Is the proper degree of flight control automation provided to allow the pilot to elevate his attention to more important matters such as tactics and threat assessment. To address such issues requires the use of a simulation with a fully equipped avionics crewstation capable of simulating the operation of the vehicle and weapons system in a mission senario.

This requires the modeling of avionics elements such as air-to-air radars, infrared sensors, electro-optical sensors, land imaging radars, etc. Reference 46 discusses one such development of a multifunction radar simulation. Not only must these subsystems be simulated, but they must also be correlated such that all displayed information is compatible one against the other and each with the "outside world" visual scene. Radar landmass simulators have been built using "terrain board-like" radar photomosaics which are viewed by a gantry-mounted camera. More recent systems are using CGI technology. A very promising long-range approach is using the Defense Mapping Agency (DMA) data base and from that generating CGI images. These images may be displayed as "outside world scenes" or filtered to resemble radar, EO, or IR displays. The DMA Level 1 data resolution is so course that only wide area coverage can be portrayed. Level 2 data has resolution to 100 feet. Most simulations will require even greater resolution which is not yet widely available. The advantage of this approach is the tremendous data base available through DMA.

3.3 Handling Qualities

In most simulation facilities, until about ten years ago, handling qualities was the largest user of simulation. Today, however, a typical simulation facility will receive about equal use by handling qualities, weapons systems, and tactics development. The objectives of the handling qualities (or flying qualities, or flight control) engineer are:

1. Inner-loop stabilization and control law development
2. Outer-loop control integration

    a. Integration of flight and propulsion controls
    b. Integration with avionics fire control
    c. Trajectory control and navigation
    d. Terrain following and/or avoidance

3. Development of stick, rudder pedals and throttle controllers
4. Development of flight displays
5. Ground handling including nose wheel steering and antiskid breaking
6. Testing of failure modes

In these simulations fidelity becomes critical. The fidelity of the math model of the vehicle/control system must be accurate and the visual and motion system, which provide cues used by the pilot in control, also become important. One of the big failings of the simulation community, however, is to rigorously define what fidelity is required to obtain the right answer. Although a large body of basic data exist on human perception (some of which will be discussed in Section 4.0) there is no source of compiled guidance on what degree of simulator fidelity must be used. The tendency has been to use the "best" simulator available. In fact, in the U.S., almost every new military aircraft developed has conducted an in-flight simulation as a last check before first flight. The experience in the in-flight simulations has quite often revealed concerns which had not been uncovered in the ground based simulations and which in some cases resulted in modifications to the control logic prior to first flight.

3.4 Pre-First Flight Pilot Training

This use of the simulator is self explanatory. The purpose of the exposure is to familiarize the pilot with the aircraft based upon the best engineering knowledge available of what its flight characteristics are predicted to be. Flight profiles will be developed and practiced. Highly unlikely and potentially dangerous events will be tried. All of this is pointed to the best possible preparation for first flight. Here again the use of in-flight as well as ground-based simulation has become standard practice.

3.5 Flight Test Support

Continuing after first flight, simulation will continue to play a role throughout the weapon system development. Flight data will continuously be analyzed and any necessary updates made to the simulation model. Pilot proficiency can be kept at a peak by augmenting actual flight hours with simulation time. Flight cards can be practiced before each test flight to maximize the utilization of time. In one simulation session many landings can be practiced where in real flight about 95% of the time is spent in circling and in taxi. Twenty to thirty ACM engagement trial can be conducted in one hour. In some very high technology developments and with large joint contractor/military test teams the amount of flying per test pilot in the early stages may be very constrained. In some extreme cases where R&D flights are especially slow paced, it is normal for the test pilots to spend 100-200 times as much clock time in the simulator as in actual flight tests (see Reference 32 and 47).

4. REQUIREMENTS

This section will discuss the major elements of a simulator; the visual system, motion system and computational system. The focus will be on aspects important to the user and not on mechanization details. But first, it is necessary to understand a bit more about the physiology of the pilot.

4.1 Human Physiology

Figure 21 shows the physiological inputs to the pilot from motion and visual display systems. The vestibular system is in the inner ear. The semi-circular canals are angular velocity sensors with a bandpass of 0.1 to 1.0 hz. The otolith organs are linear accelerometers with a bandpass of 0.03 to 0.24 hz and a threshold of 0.005 g's. The kinesthetic system senses the orientation and rates of movement of the bodies parts. Part of the position sensing are the tactile receptors which trigger nerves when the skin is compressed or released such as against the bottom or sides of the seat, the shoulder straps or the control stick. The primary receptors here are the Pacinian Corpuscles which fire at displacements as small as 10 microns and have a time constant of 1-10 msec. The human brain receives this multiplicity of signals and the exact way in which they are combined and utilized in control and decision making is largely unknown. We do know that motion cues are more important in high frequency changes and that visual cues dominate in importance at low (0.1 hz) frequencies. The vision system can evoke a sense of motion--this is known as vection.

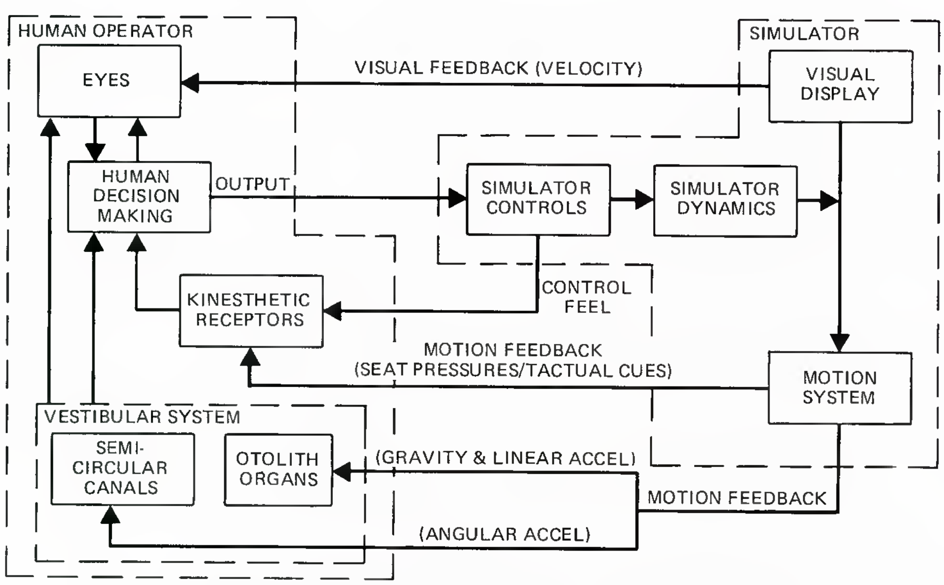

FIGURE 21. VISUAL AND MOTION CLOSED-LOOP SYSTEMS

4.2 Fidelity and Validation

We have already stated that perceptual fidelity is preferred. Perceptual fidelity is the degree to which a pilot <u>perceives</u> the simulator to duplicate the aircraft. With regard to motion, this is highly dependent upon the washouts of the human system's motion sensing. Washouts will be described in more detail in the section on motion.

For any given task, there is a cue dominance hierarchy which prevails. See references 85, 90, and 91. It has been shown that the superior cue alone leads to better performance than when combined with other cues. As a gross assessment, however, it can be said that the overall fidelity of a flight simulator can be graded as follows:

Type of Simulator	Fidelity Rating
Instruments Only	25%
With Outside Visual	70%
Also With Motion	80%
In-Flight Simulation	90%

Means have been devised of quantifying the perceptual fidelity. Reference 59 discusses three different diagnostic tools for measuring simulation fidelity all of which involve the pilot; (a) simulation fidelity rating scale, (b) pilot describing function, (c) phase plane analysis.

A lack of one-to-one correlation between visual and motion cues can cause nausea and sickness. The need for correspondence is much greater in angular (rotation) cues than in linear (translation). The tendency for motion sickness seems to be strongest for the more experienced pilots. The theory is that experience builds subconscious expectancy patterns and it is the cue conflict with what is expected that causes confusion and vertigo.

The accuracy to which a pilot can accomplish a task in the simulator is greatly influenced by the degree of fidelity. Using aircraft stabilization and control as an example, Figure 22 shows the effect of visual cues and motion cues on the ability of a pilot to stabilize an aircraft which is unstable in roll. Task performance--the amplitude of the self-excited roll angle--is dramatically effected by both motion and the field of view.

The understanding of each simulators' performance characteristics, and therefore its fidelity, is an important but often ignored aspect. Many studies are published which result from the use of simulators with not much more than a picture to describe the simulator used. The following sections emphasize the understanding required of your simulator.

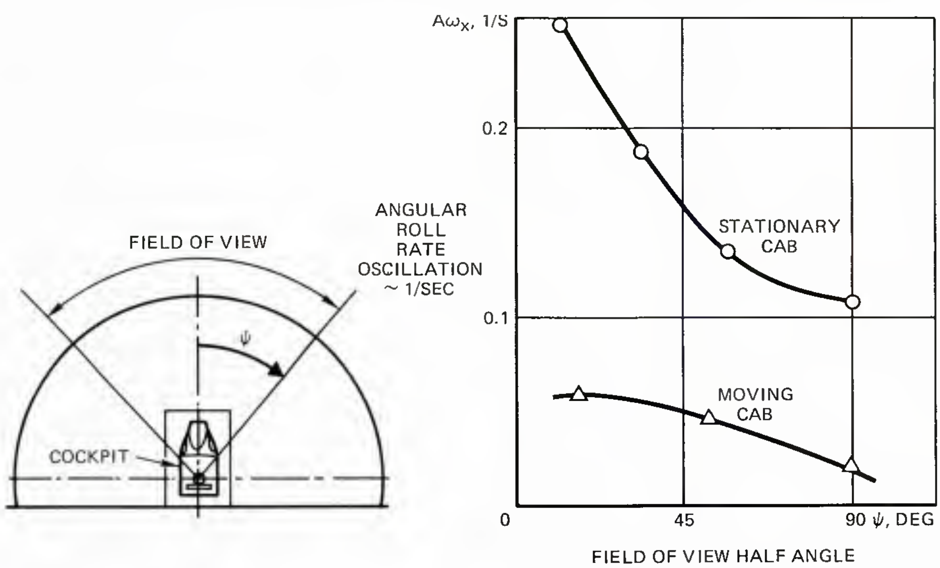

FIGURE 22. EFFECT OF FOV (ψ) AND MOTION ON CONTROL PERFORMANCE

4.3 Visual Systems

Types - The most popular visual systems start with either a model board or a computer stored data base. The image is then picked-up, processed, and displayed to the pilot as either a real image projected on a screen or as a virtual image. A virtual image is one viewed through optics. There are many optical approached (see Reference 14), however, most use collimating lenses which cause light rays to be parallel as if coming from a distant object. Subjectively, virtual images are better, however, there disadvantages are higher cost and low transmission efficiency. Most displayed scenes are of uniform resolution. There are advanced systems which have an area carved out of the regular scene and replaced by the same scene, but of greater resolution. These are called "area of interest" displays. The area of interest can be either predetermined or slaved to head or eye position (Reference 38). This concept is based upon the fact that the resolution ability of the eye is greatest in the forward (or foveal) field. From zero to about 10° off axis the cones are most dense providing a resolution of 1 minute of arc. Beyond about 15° off axis, the resolution drops to 5 minutes of arc. The projectors for these images are usually mounted within the simulator complex illuminating the screen from either the front side (as shown in Figure 23) or rear projection. Again, an advanced experimental concept is to use helmet mounted projection as shown schematically in Figure 24.

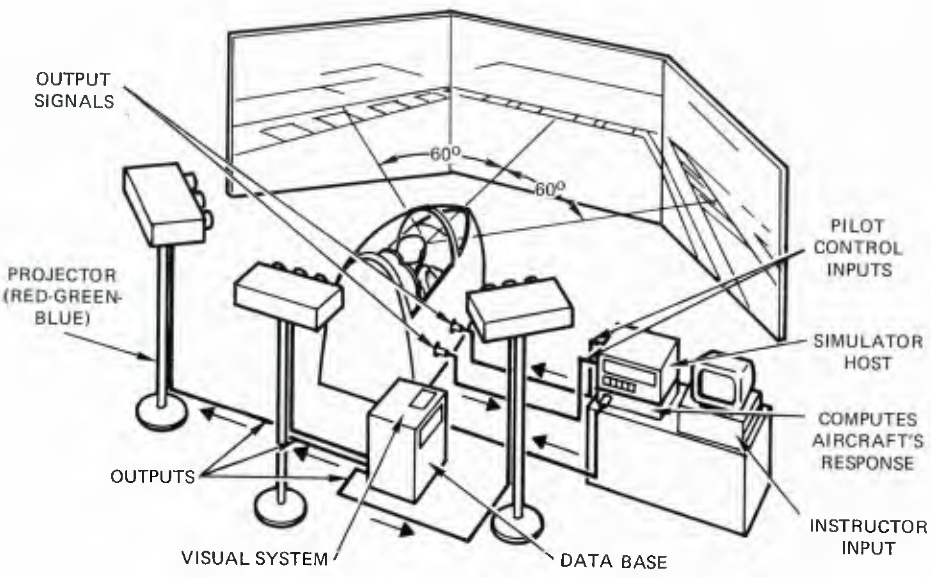

FIGURE 23. REAL IMAGE PROJECTION ON SCREENS

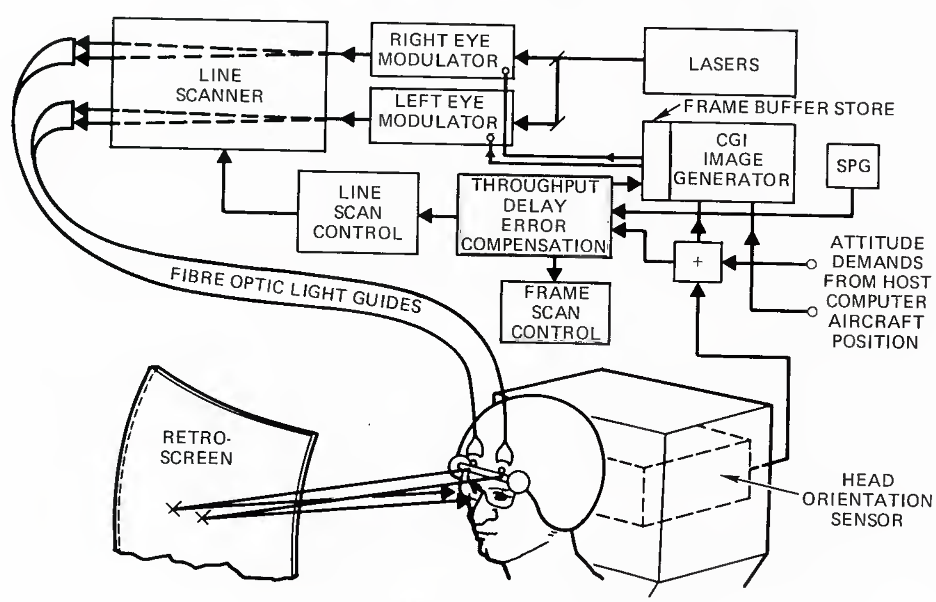

FIGURE 24. HELMET MOUNTED PROJECTION

Computer Generated Image - The CGI system is currently the most popular approach to visual flight simulators. Modern systems can display, at one time, 10,000 surfaces with texture and can store up to 10^8 surfaces in the complete model. The processing portion of these CGI systems use parallel pipeline architectures. These systems also include a host of special features such as light illumination control (day, night, dusk, etc.), horizon glow, visibility, clouds, ground fog, lightening, horizon haze, target destruction, smoke and missile exhaust trail. One of the weaknesses of CGI systems, especially for precise handling qualities evaluations, are its time delays. Depending upon the specific system selected, this can range from 50-100 msec. A concept has been developed by McFarland of NASA Ames (Reference 92) to minimize time delays in CGI systems.

Key Performance Features - Contrast, brightness and resolution are the key measures of visual systems. The popular CRT's have limited brightness. A normal room illumination is 150 candelas/m^2, whereas a CRT image after passing through collimating lenses can be about 1 candela/m^2. An F-16 training simulator was built with directly viewed CRT's. The CRT's are mounted forming a geodesic dome providing a field-of-view of 300° horizontal by 150° vertical. The pixel count, once spread over a large FOV either via a large CRT or projection on a screen results in limited resolution. Typical simulators have 512 to 1,024 pixels per line and 300 to 1,024 total scan lines. In most systems, the electron gun scans the screen sixty times each second. The first sweep of the screen will illuminate even rows, the second sweep odd rows. Therefore, a pixel is illuminated once every 1/30 of a second which is known as the "refresh rate." For low altitude high speed flight, the scene change per update is large. 600 kts. at sea level is the equivalent of 1 mile in about 5 seconds (Reference 60). However, to the eye, things are a blur at these speeds anyway. Near field resolution, however, is reported in Reference 59 to be important to perception of roll attitude and roll rate. In addition to peripheral cues, the mechanism of "streamers" or granularity and texture in the near field was found to be important to good attitude control.

4.4 Motion

The pilots perception of motion comes from a cluster of cues. The following discussion will separate these into direct cues provided by physically moving the simulator cockpit and indirect cues which are those perceptions which normally accompany motion. Examples of indirect cues are the g-suit being pressurized, being pressed into the cockpit seat or the dimming or greying of the visual scene when approaching blackout conditions.

4.4.1 Direct Motion Cues

Direct motion systems consist of the following elements:

Computed Aircraft Motion → MOTION DRIVE LOGIC → GENERATE COMMANDS TO SERVO SYSTEMS → MOTION HARDWARE → Simulator Motion

A good motion system must carefully consider each of these elements. Poor motion effects may be worse than no motion at all. Critical factors impacting motion quality are:

CRITICAL MOTION FACTORS

1. Excessive time delays and phases lags
2. Lack of synchronization with the visual system
3. Inadequate acceleration or amplitude of motion levels
4. Inadequate bandwidth
5. Washout algorithm not suited to the task
6. Jerkiness or abrupt reversals
7. Loud disturbing noises

Reference 18 is an attempt to define rigorous measures and means to quantify the performance of motion hardware. Standardizing such measurements has provided a better means for a one-to-one comparison of simulator performance. AGARD-AR-144 (Reference 12) describes in detail measurement procedures for:

1. Excursion limits for single DOF
2. Describing functions
3. Linearity and acceleration noise
4. Hysteresis
5. Dynamic threshold

One output of the AGARD-AR-144 procedure is the Motion Performance Diagram (MPD) shown in Figure 25. The MPD captures on one figure the position, velocity, and acceleration limits of a motion system. Software has been written by Delft University for the Gould/SEL to produce the data analysis required by AGARD-AR-144. The motion system is usually hydraulically powered and performance is limited by the flow rates of that system. Also shown on Figure 25 are the other constraints on the overall system such as drive logic washout effects and servo bandwidth limits. Motion system dynamic thresholds (or time delays) can be reduced to under 50 msec. by the use of hydrostatic (low friction) bearings and dynamic compensation as shown in Figure 26 from Reference 27.

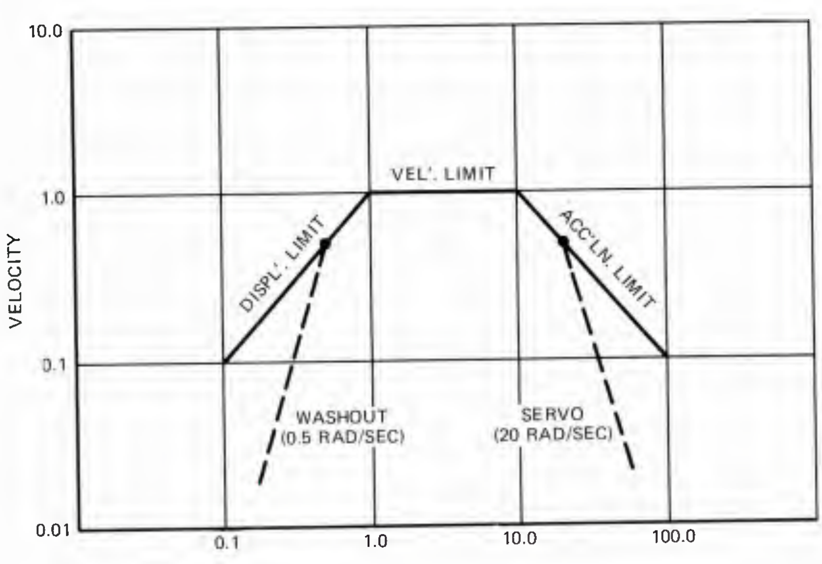

FIGURE 25. MOTION PERFORMANCE DIAGRAM

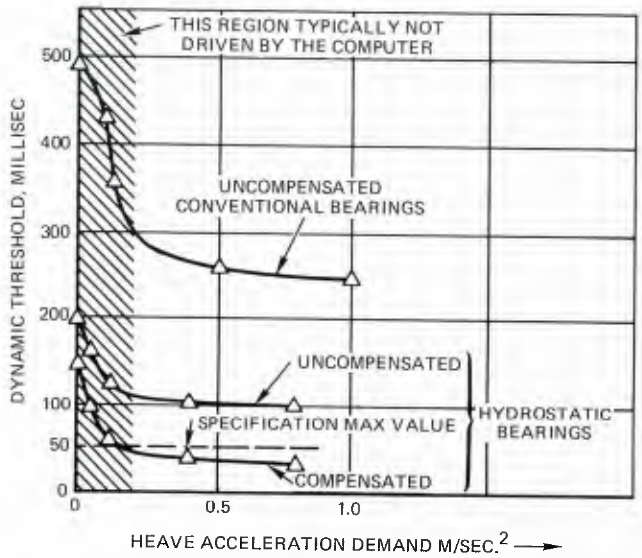

FIGURE 26. DYNAMIC THRESHOLDS OF FLIGHT SIMULATOR MOTION SYSTEMS

4.4.2 Washout Perception and Drive Algorithms

The human motion sensors typically have a "bandpass" characteristic which means they can sense motions neither at very high frequencies nor a very low frequencies. These characteristics were described under the Human Physiology section above. In vernacular terminology, this means that a pilot is sensitive to the onset of motion, but not to its steady-state level. It is this phenomena that allows limited excursion motion simulators to be successful. The visual scene picks up the long-term and steady-state translations and rotations. For fighter aircraft, a successful motion system should have a high frequency limit of about 10 rad/sec which is approximately the bandwidth of the vestibular sensors and above any manual control crossover frequencies. This sets the horsepower of the drive system. The low frequency limit should be about 0.1 rad/sec which is approximately the washout frequency of the vestibular system. This sets the excursion limits of the simulator. In returning the simulator to center, the motion amplitudes must remain below the indifference thresholds of perception which are about 2°/sec in angular motion and 0.1 g's linearly. Figure 27 shows a complex five degree-of-freedom drive logic diagram as used on the Northrop (beam type) Large Amplitude Simulator. The washout function will cause the type of time histories as shown in Figure 28. The simulator motion system will follow the computed aircraft response initially, but will gradually differ and if no other commands are issued return to its original (centered) position. The performance of the washout filter is set by its gain and frequency. These parameters are set at fixed values in most simulators. However, since the motion cue demands vary as a function of task and/or speed, the parameters can be varied accordingly to improve the overall motion system performance. The theory and practice of motion drive logic is well published in references such as Parish, and Haustmann & Vander Vart. Reference 39 discusses the use of optimal control to manage motion filters given pilot motion sensation constraints

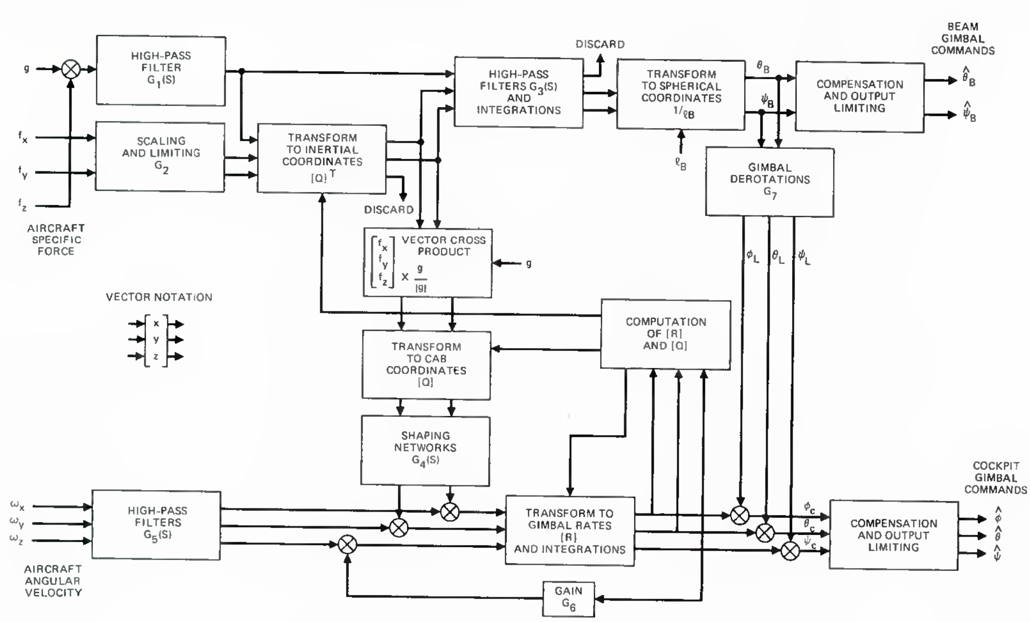

FIGURE 27. MOTION SYSTEM DRIVE LOGIC

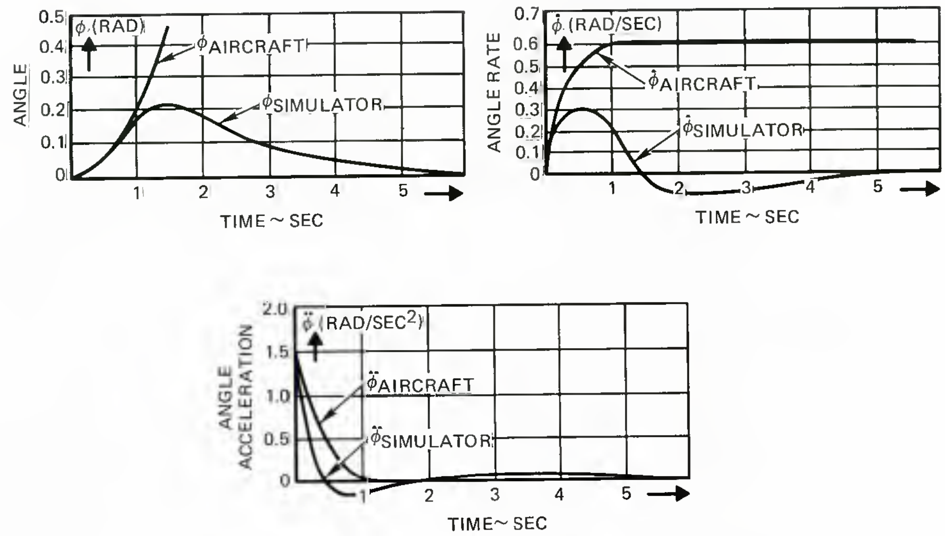

FIGURE 28. EFFECT OF A ROLL AXIS WASHOUT FILTER

4.4.3 Indirect Motion Cues

Indirect motion cues can be used either with direct motion cues to further enhance the illusion or they can be used in a fixed based simulator to partially restore both the perception and task performance of flight.

At rather low cost, one can add a vibration shaker to the simulator. This can be driven by the computer as a function of g-level, C_L, or M to simulate stall or Mach number enduced buffet. Due to human and cockpit instrument effects, vibrations are usually, $\leq$ 5hz. The visual screen can also be dimmed or narrowed in its projected field of view to simulate effects of approaching g-loss of consciousness. Such cues are naturally available in real flight and providing them in the simulator can be helpful in preventing unknowing overcontrol.

For many years, some simulators used "g-seats" to reproduce the feeling of being pressed into the cockpit seat under load factor. The seat would inflate and deflate in such a way to produce the illusion. The dynamic response of such seats was slow and therefore only steady-state effects could be produced. Recent developments (Reference 80) have shown that with a far more responsive (10 Hz) so called dynamic seat, surprising performance benefits can be gained. Figure 29 shows the results of roll disturbance tracking trials using no motion, full motion, and no motion but using the dynamic seat driven by an algorithm that reproduced the buttocks pressures associated with roll angle displacement. The dynamic seat produces performance results almost identical to that with full motion.

Anti-g suits which are pressurized in the simulator similar to the way they are in the aircraft can be used. However, they are seldom used in practice.

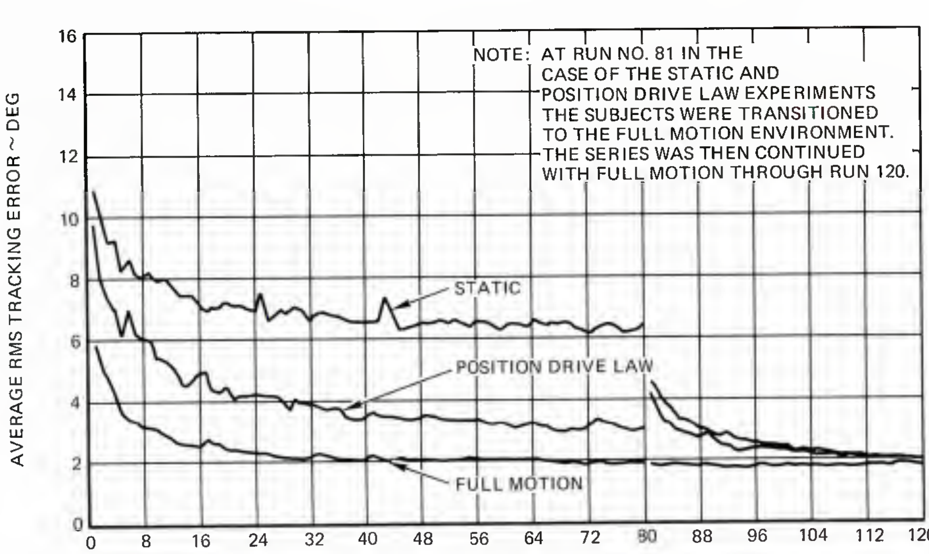

FIGURE 29. EFFECT OF DYNAMIC SEAT ON TRACKING ERRORS

4.4.4 Importance of Motion

A pilot in a closed loop control task can be described as a servo element. A typical model will include a gain, a perceptual/neuromuscular time delay, and if necessary to achieve good task performance lead and/or lag compensation. Reference 62 shows that the need for motion is a function of how well behaved is the controlled element. Marginal to control conditions such as low stability, high sensitivity or low damping require motion for the pilot to be able to generate the necessary lead compensation. Again Reference 62 shows that pilots can generate some lead compensation based on visual information only, however, he can do so only with the addition of about an additional 100 msec of time delay. Figure 30 shows the effect of the motion cue on the closed loop pilot vehicle performance.

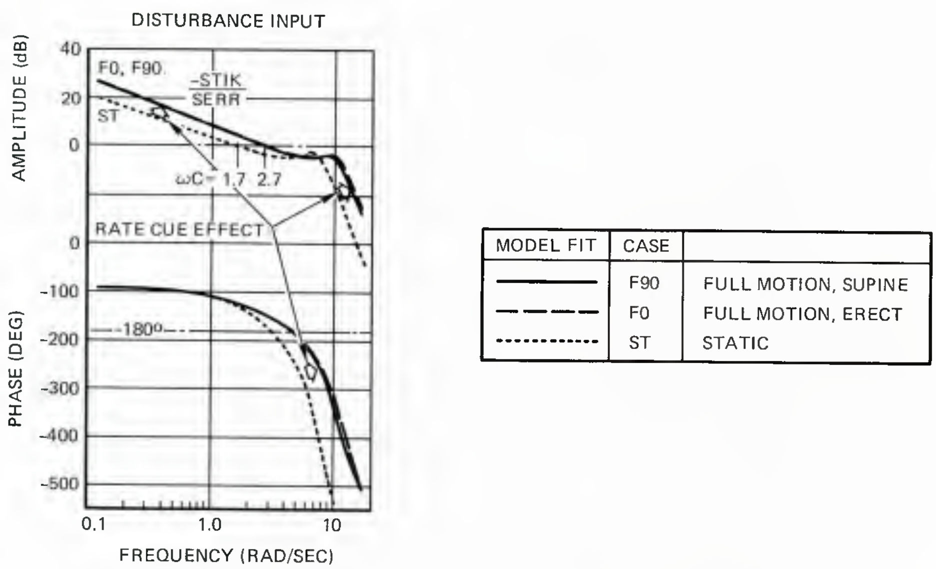

FIGURE 30. EFFECT OF MOTION CUES ON "OPEN-LOOP" DESCRIBING FUNCTIONS

The trend, however, has been toward fixed-base simulators with CGI visual systems. These simulators are very good for cockpit design and mission avionics assessments, but there is some evidence that an overreliance on such simulators has led to a series of flight control and flying qualities problems on recent aircraft developments. There have been a number of PIO problems especially in the lateral axis. References 93 and 94 attempted to define the region of preferred roll axis performance in terms of roll sensitivity and roll mode time constant. Figure 31 shows that there was a gross disagreement between the region obtained from the fixed base simulator and that from in-flight simulation. The short comings of fixed base simulation could also explain the evolution of the YF-16 roll control common gradient from that found acceptable in the simulator to that finally preferred in flight as shown in Figure 32.

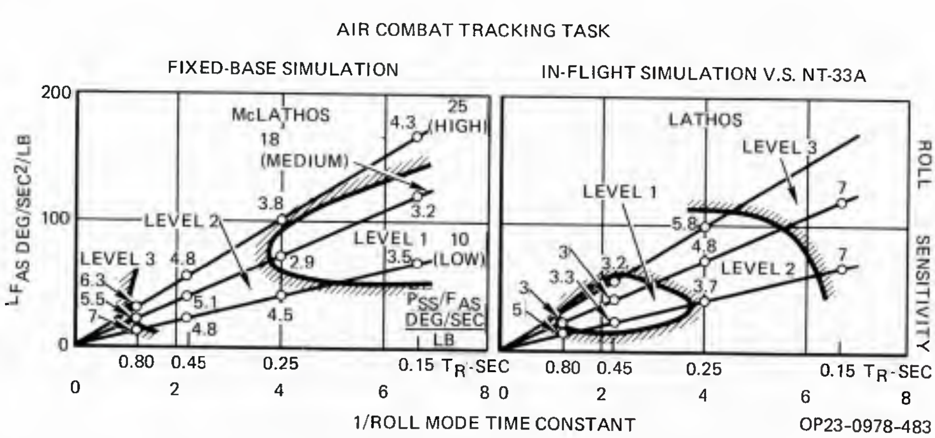

FIGURE 31. COMPARISON OF FIXED BASE AND IN-FLIGHT ROLL AXIS CRITERIA DEVELOPMENTS

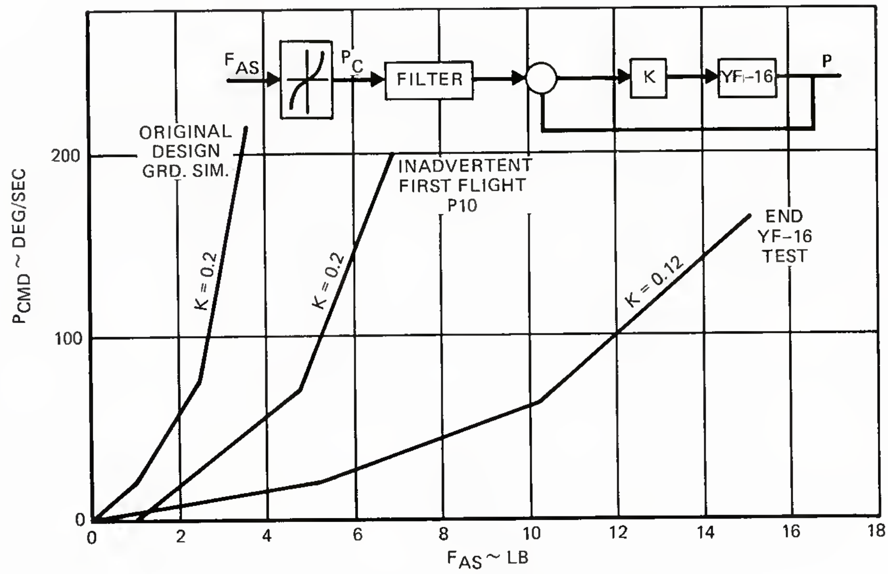

FIGURE 32. YF-16 ROLL COMMAND GRADIENT

Another interesting study (Reference 95) was conducted at NASA Ames Dryden in 1970 using the Jetstar variable stability aircraft. The task was to hold the wings level in the presence of experimentally induced "external" disturbances. The aircraft was "flown" fixed base IFR, moving base IFR, and moving base VFR for a variety of values of roll mode time constant. The performance varied significantly with both motion and visual changes as shown in Figure 33.

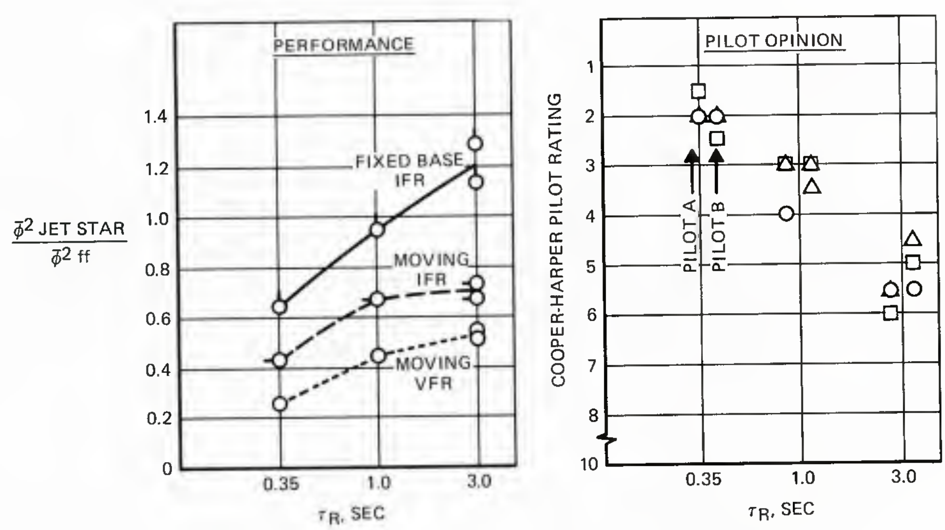

FIGURE 33. EFFECT OF MOTION ON ROLL TASK PERFORMANCE

An example of the lack of motion leading to improper pilot assessments is given in Figure 34 from Reference 59. In a fixed base simulator the pilot defines as "soft" landings up to about 7 ft/sec which in reality are quite hard.

Reference 96 documents a study conducted at NASA Ames which investigated the effect of vertical heave motion washout on landing performance. The task was final approach, flare and touchdown. The motion drive logic washout frequency was varied from "no motion" to 0.2 rad/sec which provided almost full fidelity motion for this task. This was possible because the simulator has 60 feet of vertical travel. The tasks were performed with three aircraft configurations; ones in which the pitch axis was stable, neutrally stable and then unstable. Figure 35 shows impact rate at touchdown versus the degree of motion fidelity. For the stable airplane, landing performance was invariant with motion; however, for the two difficult to control configurations there was a point at which task performance departed dramatically from the approximately full motion performance level.

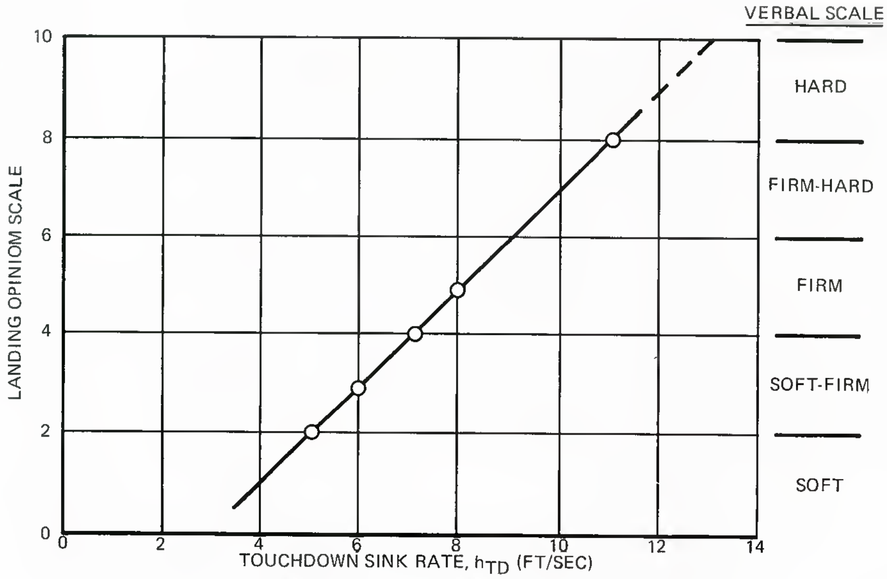

FIGURE 34. SIMULATOR LANDING CORRELATION

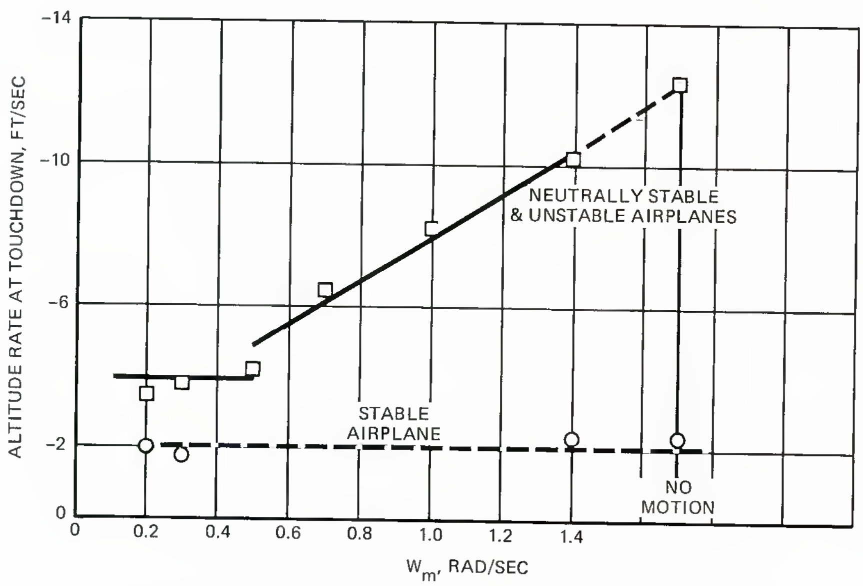

FIGURE 35. EFFECT OF MOTION ON LANDING PERFORMANCE

There is still much controversy over the importance of motion cues in flight simulation. Unfortunately, neither the user community nor the simulator developers or operators seem willing to invest the resources to answer the questions. Fundamental and specific criteria are lacking. Therefore the following advice is offered. As a general guide, one should seek the use of a motion base simulator when investigating:

1. minimum safe control characteristics
2. peak workload assessments
3. failure transient recovery
4. pilot induced oscillations
5. ride qualities

4.5 Computation

The computation portion of the simulator is typically digital and consists of multiple processors. The flow schematic in Figure 36 show cockpit interface processors, digital image generators (DIG), and a graphic processor for the cockpit displays. The main simulation processors are a set of master and slave processors with shared common memory. The software modules are listed in Figure 37 which also shows how the tasks are partitioned among the processors. High speed array processors are shown supporting slave #1 which is responsible for computation of the airframe and engine model. The array processors are used for aerodynamic coefficient and function table lookup computations. A full flight envelope aerodynamic model can require up to 150,000 data points.

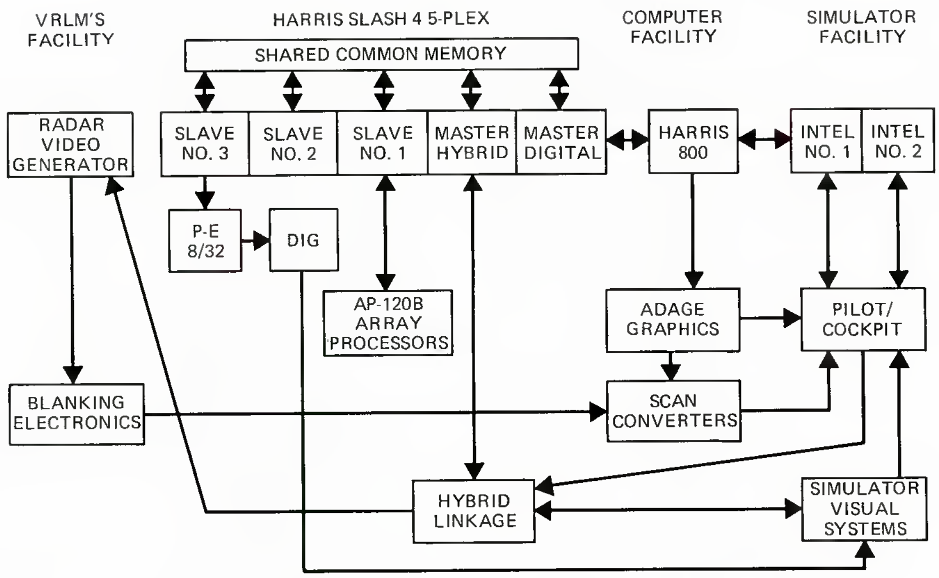

FIGURE 36. TYPICAL FACILITY FUNCTIONAL FLOW SCHEMATIC

MASTER DIGITAL	MASTER HYBRID	SLAVE 1	SLAVE 2	SLAVE 3
EXECUTIVE	EXECUTIVE	EXECUTIVE	EXECUTIVE	EXECUTIVE
MISSION COMPUTER	HYBRID INTERFACE	GUST ROUTINES	TRIM ROUTINES	INTERACTIVE TARGET
MISSILE ALGORITHMS	RADAR DRIVER	LANDING GEAR	DYNAMIC CHECK	
A/G WEAPON DELIVERY ALGORITHMS	TRACKING RADAR ALGORITHMS	AIRFRAME AERO-DYNAMIC MODEL	DIGITAL FLIGHT CONTROL SYSTEM	
GUN ALGORITHMS	SPECIAL RADAR MODE ALGORITHMS	ENGINE		
STORES MANAGEMENT	RADAR B-SWEEP ALGORITHMS			
HORIZONTAL SITUATION DISPLAY	RADAR HIT DETECTION LOGIC			
NAV RECEIVERS	SEARCH RADAR ALGORITHMS			
TACAN MODEL	AUTO-ACQUISITION RADAR			
ILS MODEL	A/G RADAR			
NAVAID STEERING ALGORITHMS	INSTRUMENT DRIVES			
HUD				
INERTIAL NAVIGATION SYSTEM				
UP FRONT CONTROL PANEL				
INTEL 8080 INTERFACE ALGORITHMS				
ENGINE INSTRUMENT				
TRACKING TARGET DRIVE				

FIGURE 37. SOFTWARE PARTITIONING

The required frame rates for the entire simulator system is a function of the purpose of the simulation. For pilot in the loop evaluations, frame rates of 50-80 hz are typical (20 - 12.5 msec/update). However, if one wants to include real hardware-in-the-loop such as flight actuators or flight control computers, then frame rates could be required from 80-500 hz (12.5 - 2 msec/update).

Standard data processing computers are not well suited to real time operation. The most common real time simulator computers are the Gould/SEL Concept 32 and the VAX, both of which are dual processor machines in the 4-5 MIP class. For extremely demanding computational tasks such as helicopter rotors or fully dynamic jet engine component models, an even faster machine such as the AD-100 with 10-20 MIP's may be required.

Software has historically been in machine or assembly language to optimize execution speed. However, in recent years, the trend has been toward the use of Fortran. Now Ada is being imposed upon the US simulation community by the USAF. The Deputy for Simulation in the Aeronautical Systems Division at Wright-Patterson Air Force Base has issued an "Ada Implementation Plan" which required the use of Ada for simulators starting in 1987. Reference 82 discusses the use of Ada for simulation. Positive features are the extensive programming support environment including a real-time debugger (to monitor and change any parameter during the run operation) and program design language. However, the best Ada compilers today are still only about 75% as execution speed efficient as Fortran.

4.6 Time Delays

The total time delay through all the elements of a simulator can be a real detriment to accurate real-world-translatable results. Figure 38 shows a representative time delay diagram. Each element adds a small amount of delay resulting in a total stick input to visual scene motion time delay of about 150 msec. This amount of delay is unacceptable. Figure 39 shows the results of several experiments mostly using in-flight simulators where delay was added to the stick-to-motion forward path. Beyond about 100 msec, the time delay starts to effect (degrade) the pilot ratings. In accordance with this data, the Flying Qualities Specification MIL-F-8785C has now included a requirement that aircraft on-board equivalent time delays due to digital processing and accumulated higher order lag effects not exceed 100 msec. This means that the simulation facility delay likewise must not exceed 100 msec.

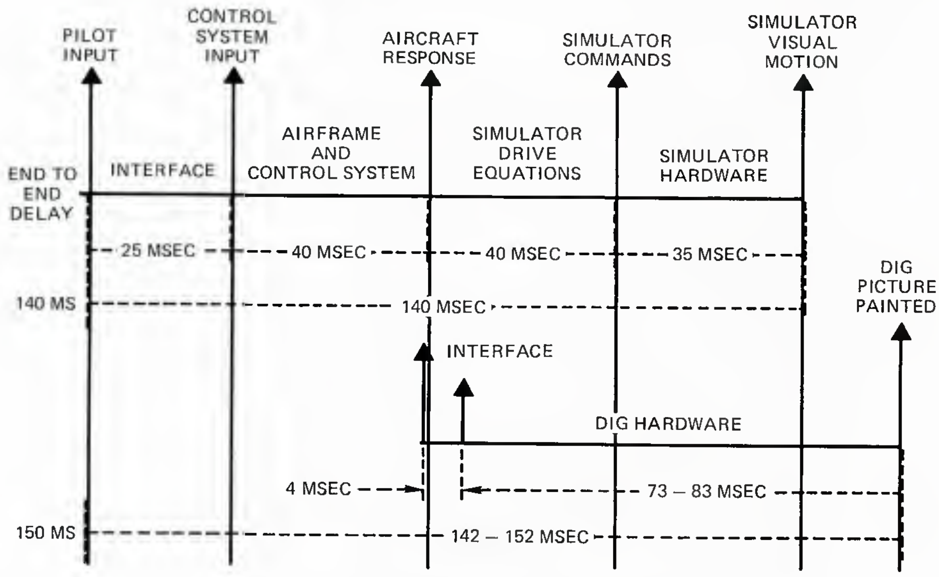

FIGURE 38. SIMULATOR TIME DELAY MAP

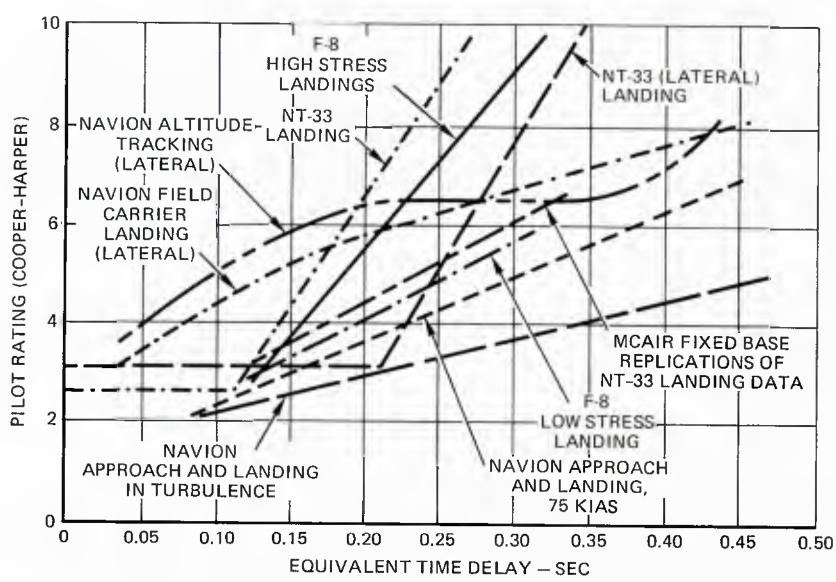

FIGURE 39. EQUIVALENT DELAY EFFECTS ON PILOT RATING

5. EXPERIMENTAL DESIGN

5.1 Critical Tasks

One of the key variables under experimental control in the use of a simulator in fighter aircraft development is the evaluation task. Tasks need to be chosen which force any hidden problems to surface.

High gain tracking is one such task. The gain referred to here is the pilot's gain. In other words, the pilot must be required to hold the pipper as tightly as possible on the target aircraft. Some experimentors like to contrive a competition on tracking scores among the participating evaluation pilots as a means to force high gain operation. Approach and landing is a demanding task, but if one is allowed a very long runway, then flares and touchdowns can be made in a very cautious fashion and problems may not surface. Offset spot landings have been used to cause problems to surface. Either a ceiling breakout or a random step offset will be introduced just a few seconds before touchdown. This requires a large last second correction. At the same time, the pilot is required to touchdown as close as possible to a predesignated spot on the runway. A similar task using a very simple display was used in Reference 97. This display is shown in Figure 40. The pilot flies the glideslope attempting to bring the airplane reference to coincide with the ground plane. However, the length of the ground plane symbol gets shorter with time. The pilot must touchdown before the ground plane symbol disappears.

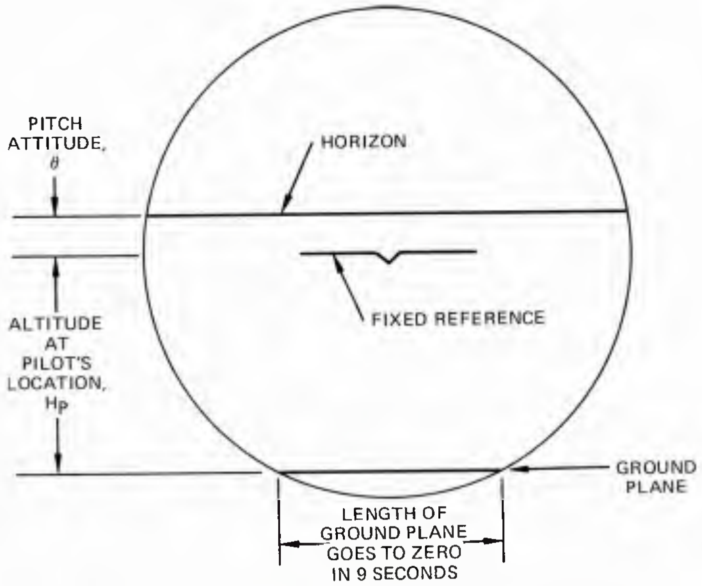

FIGURE 40. SIMULATION DISPLAY FOR HIGH GRAIN CONTROL

The use of a command bar on the HUD driven by a series of random steps or a sum-of-sine-waves is another task often used in the Calspan in-flight simulations. Aerial refueling has eluded many attempts at simulation. It has been successfully used as a design evaluation task in in-flight studies (see Reference 99), however, on the ground the task difficulty has generally exceeded the fidelity requirements of motion, visual and computational systems.

5.2 <u>Pilots</u>

It is important to select pilots familiar with the art and science of simulation. The pilot must <u>believe</u> in simulation, take the job seriously and work hard at task demands. He must treat the simulator with the same frame of mind as he would the real aircraft.

Pilots differ significantly one-to-the-other in their control techniques. Some are low gain operators making a minimum of control inputs, while others are very high gained (dither) controllers. These different control techniques may cause one pilot to have little difficulty with a configuration while another pilot may uncover a control problem. It is therefore wise to have a variety of pilots in your evaluations. A minimum number should be three (3) with five (5) or more being preferred. Multiple pilots is more important than repeat runs. Given the choice use four (4) pilots versus two (2) pilots flying each configuration twice.

The U.S. Navy requires their test pilots to have recent fleet experience to aid their ability to extrapolate flight test evaluations to operational use by the average pilot.

It is a good idea to thoroughly brief each evaluation pilot on the simulator, the evaluation task and data collection desired. It is also a good idea to describe to the evaluator the general evaluation problem and to thoroughly familiarize him in the simulator before starting evaluations.

Finally -- <u>listen to your pilots</u> -- their inputs can be extremely valuable; more revealing than the more quantitative measured data. More will be said on this subject in the section on qualitative data below.

5.3 Atmospheric Modeling

Atmospheric models for simulation can include random turbulence, discrete gusts, and wind shears. Models for these phenomena are well described in MIL-F-8785C. Of the two turbulence models defined in 8785 (Dryden and Von Karman) the Dryden model is the most commonly used because of its relative ease in modeling. The von Karman model requires fractional exponents. These models follow Gaussian probability distributions. The Tomlinson model is described in Reference 79. It is a non-Gaussian model. The Tomlinson model appears more patchy and is more frequented by large magnitude gusts. Figure 41 shows a comparison of gust velocity time histories for both Dryden and Tomlinson models. Reference 9 has documented the spectral and statistical properties of the Tomlinson model. It can be made to appear similar to the Dryden model with proper choice of the controllable parameters. Guidance in the proper selection of SIGMA, the intensity control and F the probability distribution control are given in References 73 through 78.

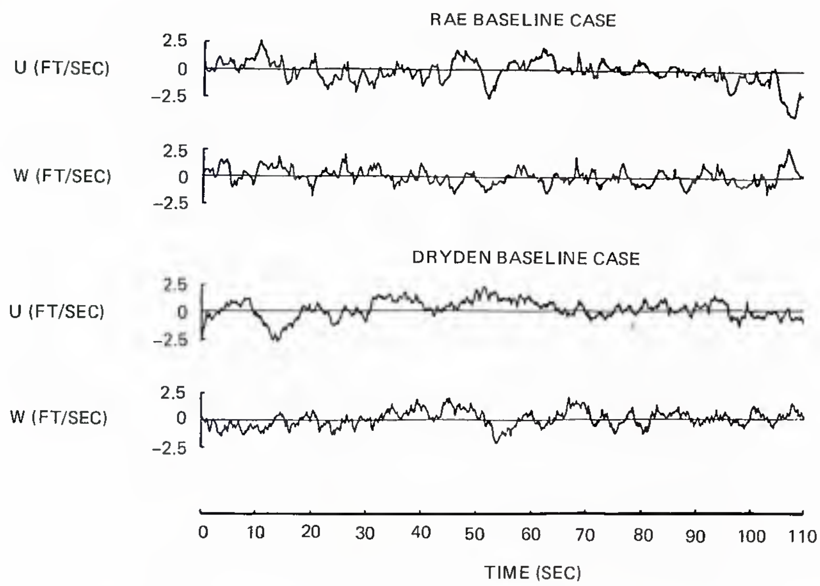

FIGURE 41. DRYDEN VS TOMLINSON TURBULENCE COMPARISON

5.4 Ground Handling

Ground handling is a very difficult problem to simulate accurately. One must transition from wing borne flight to being totally supported by the wheels; ground effects on aerocharacteristics must be considered; tire and strut dynamics and runway friction properties must be modeled.

5.5 Simulation Validation

Simulation validation before the start of any evaluation tasks should be a four-step process.

Simulation Validation Steps

1. Document simulation equipment performance
2. Conduct non-real time model checks
   (Compare to control law analysis results)
3. Conduct real time model checks
4. Conduct task checks

With regard to item 1, a good check on the validity of the simulator is to model and "fly" an existing known aircraft. A rating scale like the one shown in Figure 42 can be used to assess validity. The task checks of item 4 can be aided by measuring the pilot model to see if the pilot is behaving as expected.

If flight data is available on the subject aircraft, the identical control inputs can be run into the simulator and the resulting time histories can be compared to flight data. An example is shown in Figure 43. In addition to small excursion tests, large excursion, and combined roll-yaw tests should be conducted.

CATEGORY	RATING	ADJECTIVE	DESCRIPTION
SATISFACTORY REPRESENTATION OF ACTUAL VEHICLE	1	EXCELLENT	VIRTUALLY NO DISCREPANCIES; SIMULATOR REPRODUCES ACTUAL VEHICLE CHARACTERISTICS TO THE BEST OF MY MEMORY. SIMULATOR RESULTS DIRECTLY APPLICABLE TO ACTUAL VEHICLE WITH HIGH DEGREE OF CONFIDENCE.
	2	GOOD	VERY MINOR DISCREPANCIES. THE SIMULATOR COMES CLOSE TO DUPLICATING ACTUAL VEHICLE CHARACTERISTICS. SIMULATOR RESULTS IN MOST AREAS WOULD BE APPLICABLE TO ACTUAL VEHICLE WITH CONFIDENCE.
	3	FAIR	SIMULATOR IS REPRESENTATIVE OF ACTUAL VEHICLE. SOME MINOR DISCREPANCIES ARE NOTICEABLE, BUT NOT DISTRACTING ENOUGH TO MASK PRIMARY CHARACTERISTICS. SIMULATOR TRENDS COULD BE APPLIED TO ACTUAL VEHICLE.
UNSATISFACTORY REPRESENTATION OF ACTUAL VEHICLE	4	FAIR	SIMULATOR NEEDS WORK. IT HAS MANY MINOR DISCREPANCIES WHICH ARE ANNOYING. SIMULATOR WOULD NEED SOME IMPROVEMENT BEFORE APPLYING RESULTS DIRECTLY TO ACTUAL VEHICLE, BUT IS USEFUL FOR GENERAL HANDLING-QUALITIES INVESTIGATIONS FOR THIS CLASS OF AIRCRAFT.
	5	BAD	SIMULATOR NOT REPRESENTATIVE. DISCREPANCIES EXIST WHICH PREVENT ACTUAL VEHICLE CHARACTERISTICS FROM BEING RECOGNIZED. RESULTS OBTAINED HERE SHOULD BE CONSIDERED AS UNRELIABLE.
	6	VERY BAD	POSSIBLE SIMULATOR MALFUNCTION. WRONG SIGN, INOPERATIVE CONTROLS, OTHER GROSS DISCREPANCIES PREVENT COMPARISON FROM EVEN BEING ATTEMPTED. NO DATA.

FIGURE 42. RATING SCALE FOR SIMULATOR VALIDITY

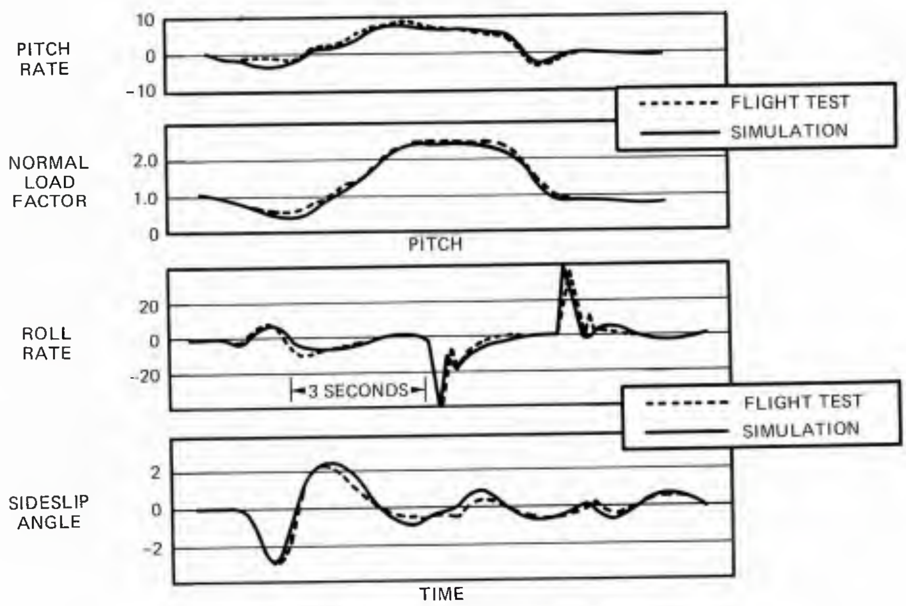

FIGURE 43. SMALL EXCURSION CORRELATION

5.6 <u>Qualitative Data</u>

Qualitative data consists of pilot ratings and pilot comments. There are several pilot rating scales. The best known is the Cooper-Harper Scale (see Reference 42) which results in a number from 1 to 10 which expresses the combination of task performance and workload required to achieve that performance. Other scales are designed specifically for PIO evaluations (Reference 99) and departure/spin evaluations (Reference 100). Pilots should be well briefed to think their way through the rating scale logic on each evaluation and not to just pick a number. In addition to the pilot rating, a series of indepth questions should be asked of the evaluation pilot. An example Pilot Comment Card is shown in Figure 44. The pilot ratings and especially the comments should be voice recorded for later analysis.

A. LONGITUDINAL CONFIGURATIONS

1. FEEL
   - FORCES, DISPLACEMENTS?
   - PITCH SENSITIVITY? - TRIM?
2. PITCH ATTITUDE RESPONSE TO INPUTS REQUIRED TO PERFORM TASK
   - INITIAL RESPONSE
   - PREDICTABILITY OF FINAL RESPONSE
   - SPECIAL PILOT INPUTS?
   - TENDENCY TOWARDS PIO?
3. AIRSPEED CONTROL
4. APPROACH PERFORMANCE
   - ILS: GLIDESLOPE, LOCALIZER, THROTTLE
   - VISUAL APPROACHES (SIDESTEP MANEUVER)
5. FLARE AND TOUCHDOWN PERFORMANCE
   - PROBLEMS? - ANY SPECIAL CONTROL TECHNIQUES?
6. DIFFERENCES BETWEEN APPROACH AND LANDING TASKS
   - SIGNIFICANT? - MOST DIFFICULT TASK?
7. EFFECTS OF TURBULENCE/WIND
8. LATERAL-DIRECTIONAL CHARACTERISTICS: A FACTOR IN EVALUATION?
9. SUMMARY (BRIEF)
   - MAJOR PROBLEMS -- GOOD FEATURES
10. COOPER-HARPER PILOT RATING (SEPARATE RATINGS FOR DIFFERENT TASKS IF POSSIBLE) - PIO RATING.

B. LATERAL-DIRECTIONAL CONFIGURATIONS

1. ROLL CONTROL AUTHORITY
2. ROLL CONTROL SENSITIVITY
3. ROLL RESPONSE IN GENERAL
4. ROLL TENDENCY TO OVERSHOOT
5. HEADING RESPONSE
   A. TURN ENTRY
   B. ROLL OUT OF TURN
6. TENDENCY TO SIDESLIP FOR ROLL MANEUVERS
7. RUDDER CONTROL
   A. POWER
   B. SENSITIVITY
8. TENDENCY OF A/C TO MAINTAIN BANK ANGLE
9. ROLL-PITCH CONTROL HARMONY
10. OTHER COMMENTS
   - RIDE QUALITY
   - INITIAL ACCELERATIONS VERSUS STEADY STATE
   - TURBULENCE EFFECTS ON RIDE QUALITY
   - MAGNITUDE OF INPUTS BEFORE ACCELERATIONS BECOME UNSATISFACTORY OR UNACCEPTABLE

FIGURE 44. TYPICAL PILOT COMMENT CARD, APPROACH AND LANDING

5.7 Quantitative Data

Quantitative data can consist of performance data such as tracking errors, touchdown dispersions or impact rates and pilot model parameter measurements. The most common form of quantitative data are statistical measures of task performance such as:

Landing Task - In an instrument landing approach one can measure deviations from the commanded flight path (glide slop and localizer angles). Fare and touchdown can be measured by dispersions from the runway centerline and from rates of sink at touchdown.

Tracking - One way to structure a tracking task is using a target aircraft in a simulated air combat encounter. For tracking error trials the target can either be preprogrammed or otherwise instructed to perform steady turning maneuvers with occasional turn reversals. This provides significant periods of steady tracking to collect data records. The pilot is asked to tightly track a specific point on the aircraft. Such trials are also frequently used in flight to uncover potential control problems. This technique is known as Handling Qualities During Tracking (HQDT) and is documented in the literature (References 101). Fast Fournier Transforms are used to identify frequency response characteristics (amplitude ratio and phase angle versus frequency) of the entire airframe control system combination. This is done by analyzing time histories of control inputs and pipper motions in these highly structured tracking tasks. Analysis of these frequency response records often reveals the nature of aircraft control problems.

An even more structured task is to insert signals into the command bar of the cockpit ADI. Random pitch or roll commands as either steps or a sum of sine waves can be used. In the case of discrete step commands revealing measures are time to capture the command (reach and stay within 10%) and the ability to stay at the commanded point during steady periods between steps.

Disturbance Rejection - This task can either be conducted IFR or VFR. In either case a turbulence like disturbance is inserted upsetting the aircraft attitude. The pilots task is to try to restore the aircraft to its original--normally level--attitude. The disturbance is normally not an accurate turbulence model because a pilot's strategy is often simply to "ride-out" disturbances of that type. The disturbance used here is most often a simple sum of three (3) to five (5) sine waves.

Air to Ground Weapon Delivery - For the delivery of unguided bombs, one can analyze the tracking errors of pipper to target. However, for most bombing systems, the task is not to keep the pipper on the target, but rather to bring the pipper to the target at the proper instant of release. Therefore release point variations and then of course the accuracy of the final weapon impact point relative to the target are the ultimate measures. An interesting phenomenon here is that it is common for pitch axis problems to show up as worsening azimuth misses and for lateral-direction control problems to show up as increased errors up range and down range. This is apparently due to the pilot devoting more of his attention to the problem axis and therefore allowing the errors to show elsewhere.

Air Combat - Air combat trials can be run when two aircraft simulations are operated interactively. The second aircraft can either be manned or it can be driven by computerized logic making pilot like offensive and defensive maneuvers based upon aircraft relative state information. Such a computerized interactive target is described in Reference 102. Quantitative measures other than outcome exchange ratios is difficult because the task is inherently unstructured. In addition to exchange ratios other measures successfully used are time to first shot and successful rounds fired to total shots.

Pilot behavior is the other measurable entity in simulation. For structured, time invarying tracking tasks pilot describing functions can be measured. In this way, one can determine if the pilot is applying compensation to correct for vehicle deficiencies. The fact that a pilot is applying compensation is often subconscious. The compensation results in good task performance and unless the pilot is very perceptive of this own behavior, it may not show up at a recognized increased workload or lowered pilot rating. A sidetask can be used to divert pilot attention. The amount of pilot attention that can be diverted while retaining satisfactory performance on the primary task is a measure of the quality of the vehicles controllability. One such sidetask is the control of an unstable mode where the degree of instability automatically seeks its maximum, while controlled level of instability. The degree to which this sidetask plant can go unstable is therefore a measure of goodness of the vehicle under evaluation. More information about the use of sidetask techniques can be found in Reference 91.

5.8 Failure Modes and Effects Criticality Analysis

An important part of a new aircraft development is not only the controllability of the system in its normal mode of operation, but also controllability in its failure states. A part of the process to investigate failure states involves the use of pilot in the loop simulations. The first step is to document the failure states. U.S. Military Specifications allow the possibility of single point failures if they can be proven to be "extremely remote" (roughly taken to be equal to the probability of failure of primary structure). Failures which cause loss of aircraft or loss of mission are acceptable provided they are below certain probability of occurrence per flight thresholds. The next step is to identify critical failure states and the flight conditions in which they are most critical. The transient effects of specific hardware failures can be determined from hardware in the loop simulations. Modern day "iron birds" or flight control system test stands are being constructed with automated test capability. This allows a greater number of conditions to be tested in the time available than has previously been possible by completely manual tests. It is possible to have a good pilot in the loop simulator tied directly to the iron bird in which case failure effects with pilot in the loop can be tested directly. However, quite often the "iron bird" and the projects flying qualities pilot in the loop simulator are separate facilities. If this is the case the iron bird tests and data from other sources allow one to determine test cases for use in pilot-in-the-loop evaluations. The failure transients and the characteristics after the failure are fed to the pilot-in-the-loop evaluations. In the pilot-in-the-loop tests, one is concerned with (1) can the pilot sense the failure transient in a meaningful unambiguous fashion, (2) does he have the means to take corrective action in response to the failure, (3) given successful transient recovery can the pilot extract himself from the given flight conditions, return and land. It is especially in these degraded control conditions that simulation fidelity is critical to meaningful results.

5.9 Users Cost

Acquisition Costs - A simple fixed based simulator with a good real time computer can begin at about $1 million. A large vertical motion simulator can cost from $3.5 to $20 million. The ballpark cost distribution are as follows:

Item	Simple Fixed Base Costs	Large Vertical Motion
Computers	$ 0.50 M	$ 3.00 M
Visual System	.15	6.00
Cockpit	.10	2.50
Instruments	.10	.50
Force Loader	.15	.30
Motion System	--	* 2.50
	$ 1.00 M	$ 14.80 M

* NOTE: $2.5M if a custom-made large amplitude system. An off-the-shelf, 6-post synergistic system is about $0.3M.

Operational Costs - The operation of a large aerospace simulation facility is an expensive proposition requiring a staff of 100-200 people. This includes skills such as electrical and mechanical designers, shop craftsmen and technicians, programmers, test technicians and test engineers. However, the cost is still far cheaper than flight testing. To fly an F-16 costs about $5,000/hr. To fly the F-16 training simulators costs about $500/hr. An extremely complex simulator operation such as the U.S. Naval Air Development Center's centrifuge costs about $700-1000/hr. This 10:1 cost advantage can be further increased when one considers that more task evaluations can be run per hour on the simulator than in flight. Reference 81 claims that in the case of large aircraft such as the 757/767 and for flight deck development where medium complexity simulators can be used the cost advantage is approximately 100:1.

6. PROJECTED FUTURES

All the projections made below are on the horizon, showing promise and have the potential to significantly affect the future of simulation in the relatively near term.

6.1 Large Scale Multi-Processors

Figure 45 shows a schematic of computer architectures. Digital processors for real time simulation have progressed from single processors to dual processors, to dual processors aided by array processors. There are currently many competing concepts for highly parallel or multi-processors. Experimental units with from 24 to thousands of processors are in test. Such concepts promise large improvements in throughput, but are hampered by programming difficulties associated with problem partitioning. If this problem can be solved, such machines should greatly aid computationally intensive real time simulations. Such computers would also provide a computational facility which can be incrementally upgraded in computing power.

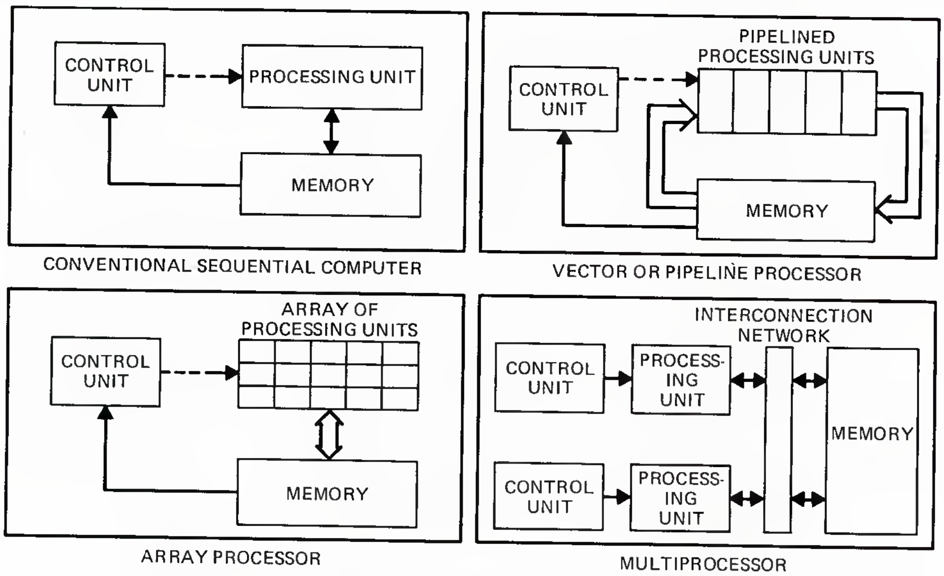

FIGURE 45. COMPUTER ARCHITECTURE COMPARISON

6.2 Helmet Mounted Displays

As technology allows the helmet weight to decrease, it is likely that helmet mounted projectors and/or displays will come into wider use. Such systems can reduce facility costs and result in improved 360° vision.

6.3 New CGI Data Base Approaches

Currently, the cost of developing a Computer Generated Image (CGI) data base is very high. NASA Ames has recently developed a set of user friendly tools to aid in the rapid development of new scene models. Ames personnel were recently able to code the Moffet Field runway, surrounding area and all buildings in about 3 man-months. Another approach will be to utilize the Defense Mapping Agency world digital data base. Moving map displays are already available using DMA data and experimental 3-D displays have been tested.

6.4 The Use of Ada Software

Ada, the U.S. Defense Department's standard high order language, is very appropriate for real-time, multi-tasking. The language is block structured and module oriented. This means that exactly one entry and one exit is permitted per block or module. It is high level and supports reusable code constructs, parallel processing, and allows the infusion of low level programming. At this time, the available compilers result in somewhat speed-inefficient code; however, this should improve with compiler maturity. See Reference 82 for more information.

6.5 Future In-Flight Simulators

The RAV concept (see Figure 15) offers to provide lower cost and more flexible in-flight simulations. Aircraft can be easily modified to operate as in-flight simulators using RAV especially if the aircraft already has a FBW flight control system. Also very powerful large ground computers can be used.

A new fighter in-flight simulator is being developed in the USA using an F-16 airframe (Figure 46). The aircraft will be called VISTA and it will have a digital model following variable stability system.

FIGURE 46. NEW VISTA IN-FLIGHT SIMULATOR IN DEVELOPMENT

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FLIGHT TESTING OF FIGHTER AIRCRAFT

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SUMMARY

The scope of this paper is to give a realistic overall picture about flight testing of fighter aircraft today and trends for the future. It is shown whether, where and to what extent flight testing is and will be necessary. Especially the implications of advanced fighter aircraft concepts on the test program are discussed regarding the high technology standard of the complete weapon system and the operational requirements.
It is concluded that best equipped facilities together with a well organized management are mandatory. The introduction of up-to-date scientific computer systems and the development of new software seems to be a permanent requirement to handle the streams of data which confront the flight test engineer.
Early plannings and preparations are required to integrate as many tasks as possible per flight in order to save expensive flying time.
Finally an overview of flight test disciplines is given. It is shown that flight test is an universal discipline. Consequently areas of main test effort only and corresponding test methods to be applied are discussed in more detail.

1. INTRODUCTION

The entire history of aviation development can be seen as a dynamic quest to turn ideas and theoretical concepts into reality; flight testing plays hereby always an essential role. The 2500 flight tests of Otto Lilienthal with his glider from 1893 to 1896 stand for one of the most important milestones in the history of aviation. These tests and the resulting experiences led to the first successful flight of a powered airplane with Orville Wright on board in 1903. This flight paved the way to a tremendous evolutionary process for the aviation in the whole world.

Today flight test is still an essential phase and the final stage in a complex development/test process of new aircraft projects. Experience gathered in the past has shown that even the current advanced prediction methods, model techniques, wind tunnel tests, pilot-in-the-loop simulation facilities and full scale static test rigs cannot replace the flight testing of a full scale test vehicle.

This is particularly applicable for the development of advanced fighter aircraft as evident by the current technology demonstrator programs in Europe and the USA.

During these development programs novel airframe configurations, composite material for primary structures, digital fly-by-wire control systems and integrated avionic and weapon systems have to be tested and integrated into an optimized military air vehicle within a defined cost and time frame.

This situation means a tremendous challenge for a flight test organization because of the following facts:

- Limited budget and tight development schedules need a flexible test organization and the performance of a most economical flight test program.

- Advanced test data recording- and processing systems and analysis methods are required in order to provide reliable and sufficient data for the system engineering disciplines in short time.

- Advances in technology as mentioned above require new and corresponding test procedures and test techniques.

The key to success to these challenges is the proper understanding and application of the principles of flight testing, which will be discussed in this paper.

2. CATEGORIES OF FLIGHT TEST

Flight testing of fighter aircraft is a continuous process which can be distinguished between 3 or 4 main categories as shown in figure 1.

CAT 1 trials consist of development and evaluation testing. These are generally industry or company trials but a certain participation by the customer is usual today. Development flight testing is the subject of a completely new weapon system, new aircraft components, modifications to aircraft or aircraft subsystems. Starting from a preliminary flight clearance, based on theoretical investigations, including simulations and the approval by the official airworthiness departments, the flight envelope will be explored step by step. Flight test measures inflight the actual characteristics and quality of the system and interprets the results in relation to the requirements. Suggestions of product improvements, modifications and alternations in order to achieve a satisfactory air vehicle are worked out during these trials when necessary.

It is important that these informations are presented in suitable test documents to the design offices in order to define and introduce modifications quickly. Finally, the flight test results are used by the development departments to re-check and refine their assumptions and predictions.

When the test vehicle has achieved an acceptable stage of development, trials will concentrate on evaluation flight testing. Operating instructions, functioning, characteristics, handling and performance are assessed within the whole operational flight envelope. Data gathering for the flight handbook and the definition of limitations for service operations are prime aspects. A comparison between final flight test results and the requirements of the customer (usually specified in the Air Vehicle Specification) will be given.

CAT 2 trials are conducted by the official test centers of the customer within the cleared envelope derived from CAT 1 trials. They examine the weapon system related to the mission requirements, check the performance of systems and whether maintenance and logistic procedures are adequate. As a result of CAT 2 trials the weapon system is declared for Release to Service.

Contractor-(CAT 1) and official-(CAT 2) trials are often combined to give the customer an early look at the aircraft (official assessments during a development test phase) or in the interest of saving time and money (eliminating duplication of tests).

After release to service, CAT 3 trials follow at the forces with respect to operational missions, including determination of operational capabilities and deficiencies, development of operational tactics and refinement of logistic, maintenance and training requirements.

Finally, CAT 4 trials should just be mentioned here; they are conducted by the forces in a warfare environment in order to gather experiences under these conditions and to define relevant regulations.

In the following the flight test principles related to the CAT 1 trials will be discussed mainly, because this test phase is the most demanding program and covers a wide range of test aspects of a fighter aircraft.

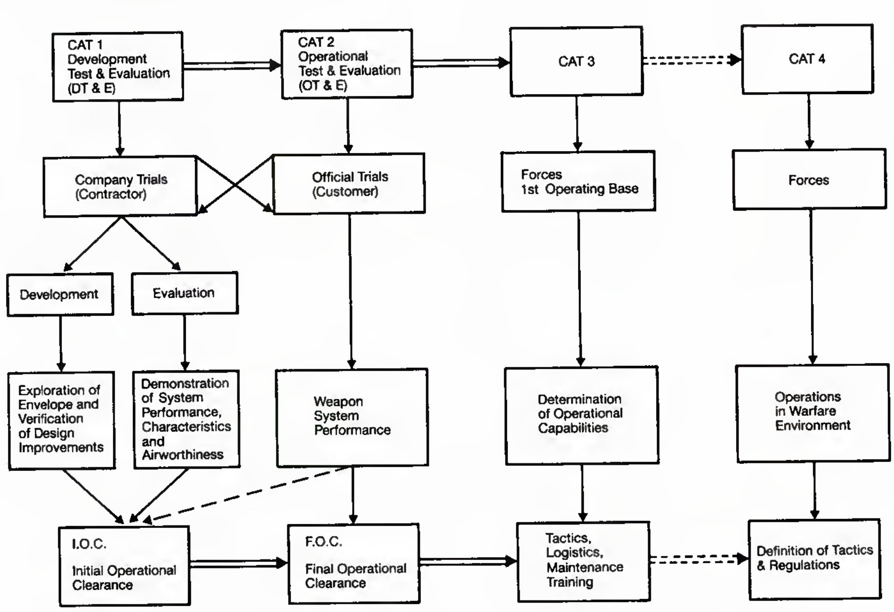

Fig. 1 - Overview of Flight Test Categories

3. ORGANIZATION

A modern flight test organization should not have a flight operating and data gathering function only; it should also have the engineering ability to cooperate with the development department when product improvements are necessary and not at least to assure flight safety. Safety must have top priority during all test activities to avoid endangering of human life and valuable products. We must have in mind that the total loss of a test vehicle means a loss of about 50-100 million US dollars which can jeopardize the total development program of a project.

In this respect flight test today has grown up to an universal discipline which has to cover a number of different branches as shown in Fig. 2. Hence, typical flight test organizations comprise flight test instrumentation, analyses engineering, test conducting, flight operations, maintenance and quality assurance (whereas the later two are often provided by other organizations). For the effective realisation of a flight test program a well organized and flexible test team is the key to success.

In order to assure the safe and efficient conduct of the overall flight test program the position of flight test within a company should be independent of the development departments. Flight test must retain its autonomy to provide independent audit of the achievement of the design goal. This is an important aspect for the project management of a company as well as for the customer.

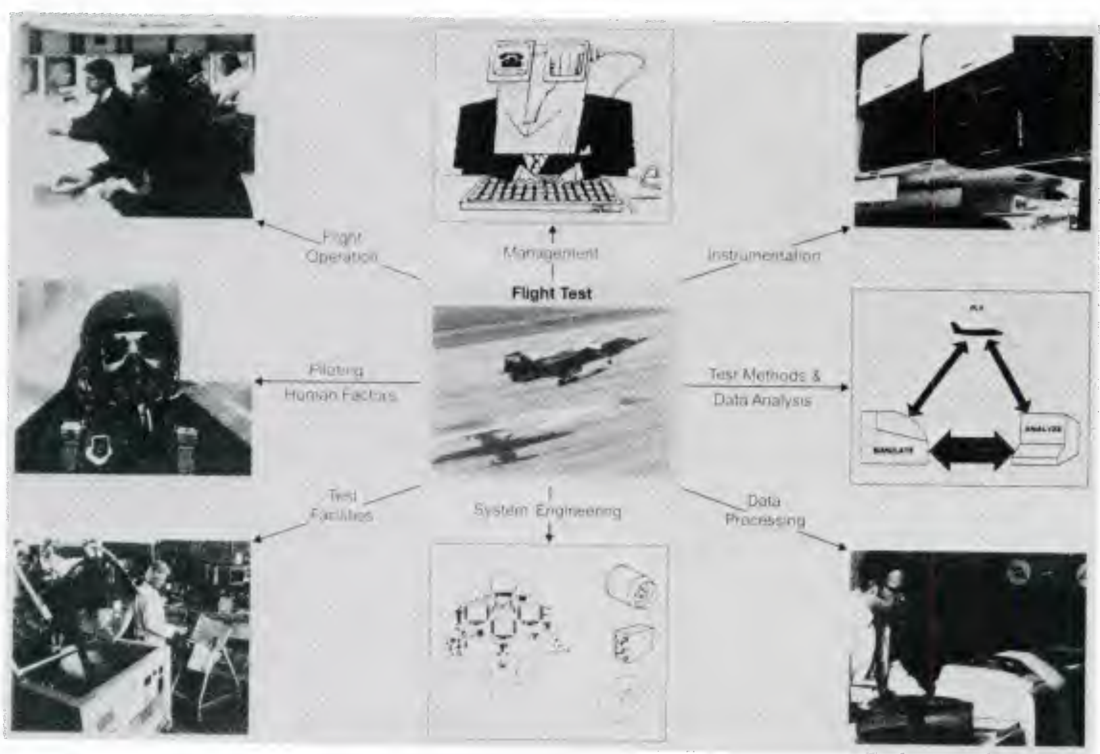

Fig. 2 - Flight Test Organization

4. PREPARATIONS AND ASSUMPTIONS FOR FLIGHT TESTING

The preparations and planning activities of a flight test program have to be started already during the definition phase of a new project. Inadequate attention to details in the long lead planning will limit the cost effectiveness of the test program and will result in the production of reams of data which do not satisfy the flight test aim to clear the system for what it is designed for and within the cost- and time frame as committed by the program management and customer.
Since most fighter aircraft programs are cooperative or international projects, an Overall Flight Test Program Management, a Test Program Control Procedure and Customer Participations have to be defined and established.

Initial plannings, definitions, estimates, assumptions and intensions are summarized in the so-called Flight Test Program Requirements. They are used as a baseline for the technical documents for the definition of the overall flight test program. As time goes by, until approximately Roll Out of the first prototype and as more informations become available, an iteration process will lead to the detailed Flight Test Information Sheets and Test Programs for the individual tasks.

Further important subjects of preparations are:

o Definition of a full-scale development flight test plan (see para 4.1).

- o Definition and procurement of a test "data production" system comprising flight test instrumentation system, ground based data processing facilities and data analysis software (see para. 4.2).
- o Definition and procurement of required test support facilities (i.e. test area and ranges, airfield equipments, chase and target aircraft, ground test station, etc.).
- o Definition and procurement of airborne facilities, i.e. test noseboom, emergency power system for high incidence tests, spin recovery device, calibrated engines, flight refueling probe, cameras and video recorders at certain aircraft locations, devices for flow investigations, special cockpit panels and displays, flight flutter equipment for excitation of wing, fin and foreplane, audio warnings, flutter stores and a variety of external stores required for carriage trials, jettison, releases, firing, functioning, weapon delivery demonstration and electromagnetic compatibility tests.

4.1 Full Scale Flight Test Development Plan

Flexibility is a key factor in scheduling flight test programs, because it is usual, that test plans have to be modified continuously during a development phase due to program delays, configuration or subsystem changes or later due to test results.

Flight test schedules and required test vehicles are based on customer milestones (IOC, FOC or delivery to service), first flight dates of prototypes or production aircraft, engine or system delivery dates and expected flying rates. Keeping the required amount of flying as low as possible is mandatory because test flying is expensive. The optimal integration of several tasks per flight is important.

However, in the case of a multi-role fighter test program, individual program elements set the priorities leading to a schedule on an interactive basis. For example flutter test requirements precede full envelope flying and satisfactory system functioning. Flying qualities and performance tests are dependent on engine/intake compatibility and engine handling/performance. Customer milestones such as official assessment phases influence the priorities of program elements and may place time constraints on the successful completion of the development and evaluation trials.

Fig. 3 gives an example of the test schedule for a typical fighter aircraft development program.

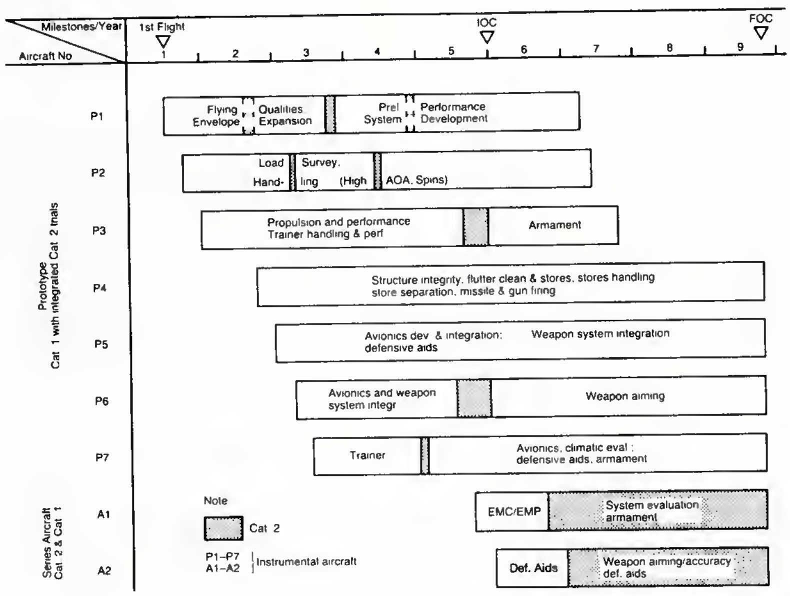

Fig. 3 - Typical Full Scale Flight Test Development Plan

4.2 Flight Test "Data Production"

One area in which flight test has made considerable improvements in the state-of-the-art is the data processing and analysis, which can be divided into three steps as shown in Fig. 4

- Onboard data acquisition (including test vehicle instrumentation)
- Telemetry and real time data processing
- Data analysis.

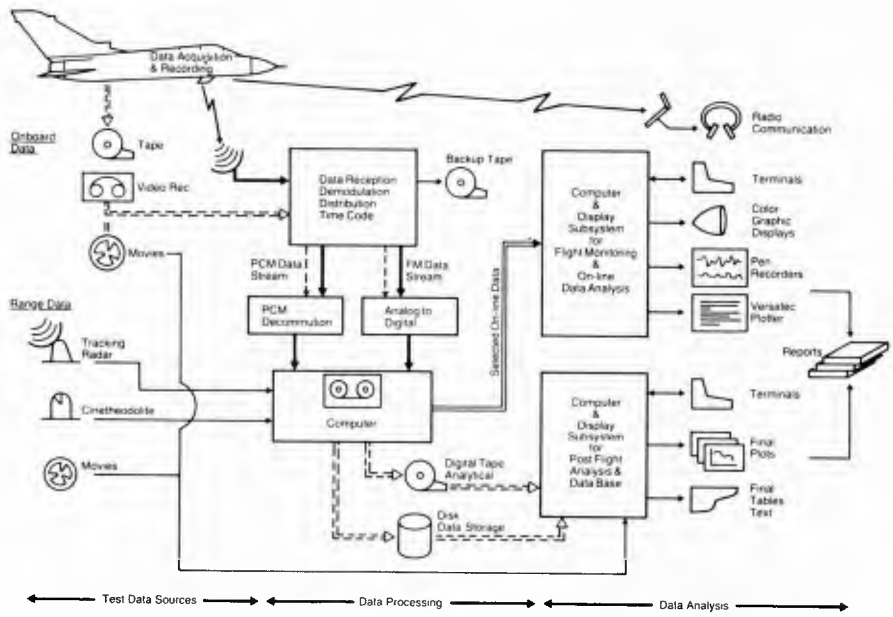

Fig. 4 - Flight Test Data Production and Data Flow

Such a system is absolutely a prerequisite for an advanced fighter aircraft program to accomplish the test trials in short time and to minimize risks on safety critical tests (i.e. flutter, high angle of attack, spin trials, etc.) because this method provides real time/online data as time histories or cross plots and allows report quality data to be available during the tests or within some hours after landing.

4.2.1 Onboard Acquisition and Instrumentation System

In the last two decades the required number of digital parameters on magnetic tape recorders has increased significantly from about 100 parameters in 1960 up to 1000 or more (F14, F18, Tornado etc.) in the seventies.

Today and in future the use of analog and discrete signals is declining. For example the next generation of fighter aircraft avionic system will have only few discrete signals with respect to the large amount of data that will be transfered via multiplex buses. With this in mind, there is a shift away from instrumenting individual signals in favor of recording the multiplex bus data streams.

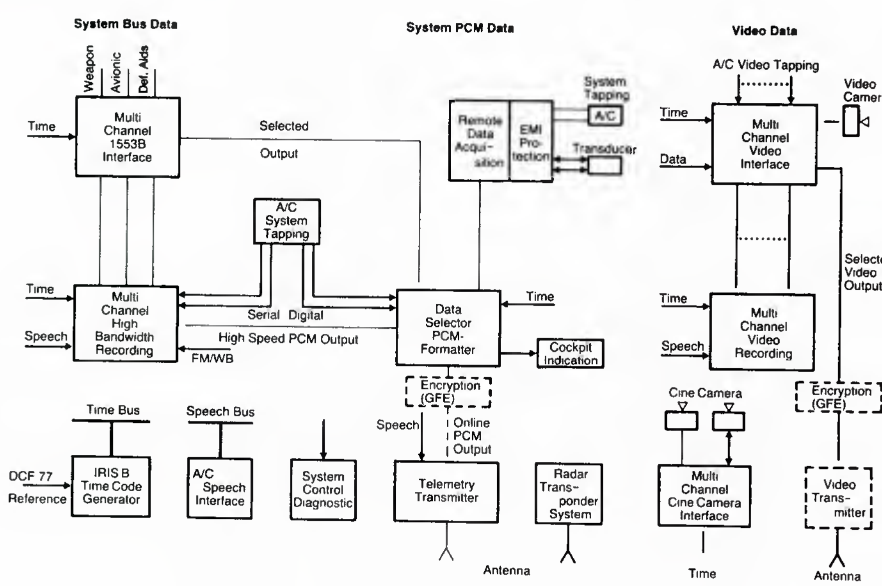

Fig. 5 - Onboard Data Acquisition System .

Further new trends are to make extensive use of video recorders (size and cost advantages) for recording of video signals from cameras, aircraft system tappings and data bus streams.

Flight testing of advanced fighter aircraft often requires encrypting of transmitted signals by means of government furnished equipment.

Fig. 5 illustrates a typical advanced onboard data acquisition system.

4.2.2 Telemetry and Real Time Data Processing

According to the airborne acquisition system the ground station must be sufficiently potent to cope with the resulting high and intensive data rates. Data telemetered from the test vehicle must be processed, calibrated, scaled and displayed in real-time/on-line in the Test Control Room on graphic displays, pen recorders, UV-recorders, plotters, line printers and on a number of terminals as shown in Fig. 6.

Here, flight test engineers monitor telemetry data to assess the quality of test manoeuvres and data, to assist the pilot from test-point to test-point and not at least to provide safety by monitoring critical system parameters.

Besides this the ground station data processing system produces analytical parameters for complete test evaluations and analyses. Fig. 4 is an illustration of an advanced processing system as usually used in fighter aircraft testing today.

Fig. 6 - Flight Test Control Room

4.2.3 Data Analysis

Normally two types of flight test data analyses can be distinguished, which must be addressed to achieve a complete data analysis system:

- Real time telemetry data analysis
- Post-test analysis.

Each of these analysis modes are needed for specific types of flight testing.

Analysis in the real-time telemetry mode is necessary for example during a time constrained program of critical structural/flutter, high angle of attack/departure or spin testing where flight hazards may exist. Today such a technique is straight forward and can be regarded as state-of-the-art (see Fig. 4).

But presently there is a clear trend in the flight test world to extend the use of real time data analysis rigorously to all analysis test discipline areas by taking advantage of the capabilities of advanced computerized ground station systems networks (see Ref. 1 to 2) for the benefit of quick and precise data presentation.

Typical application areas for example are the determination of performance data, handling/aerodynamic derivativa, engine/intake performance data or certain subsystem performance data.

Post-test analysis has historically been and will still be in future the method, by which bulk data processing, complicated engineering analysis work (iterative or correlative processings) are involved. Typical areas are parameter identification or certain engine/ performance/handling investigations, where high data accuracy or specific final report quality data and comparisons with predictions are required.

A typical network of a post test analysis process including data reduction, analysis and comparison of test data with predictions shows Fig. 7 for a complete engine/flight performance analysis.

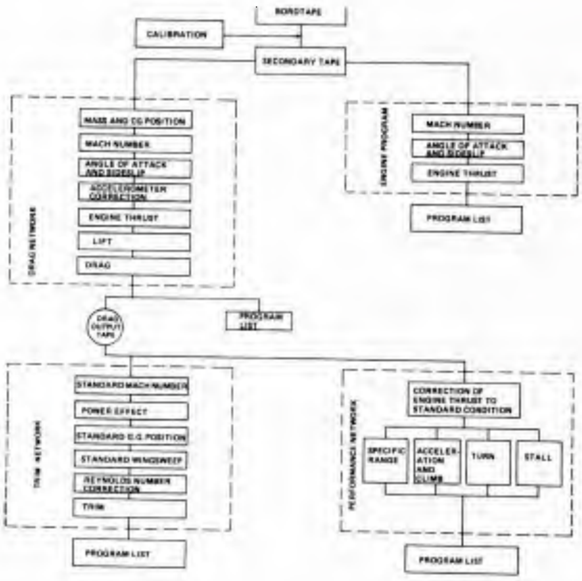

Fig. 7 - Performance Data Analysis Software Network

Only such systems and procedures of "data production" are in the position to support the test requirements for today and the next fighter generation, to minimize the amount of final reduced data gathered during a fighter-aircraft/multi-year program and to reduce data processing costs and man hours significantly. The extensive use of computers for data production will allow a few key engineers to handle high quality, accurate data in a fraction of time otherwise required by an army of engineers without such tools.

Appropriate computer hardware is available off the shelf world wide but, the required software has to be individually developed or adapted by the flight test team. As mentioned already in para. 4 the installation of the software has to be prepared as early as possible for a project to have a reliable system available when it is needed.

5. PERFORMANCE OF FLIGHT TESTING

5.1 Test Procedure and Sequential Course of Flight Trials

In principle the test conditions are approached logically step by step. Hence, test points will be flown with increasing complexity/risk and environmental factors (i.e. increasing speed/Mach number, higher g-load, lower altitude, increased weight/external stores, etc.) in order to explore and expand the flight envelope systematically.

Fig. 8 shows the typical sequential course of a test mission. The test program and test points (manoeuvres) are defined by the flight test engineers. From these the flight test conductor prepares the flight cards and briefs the test crew. Generally the test pilot is responsible for conducting the test flight. He makes the final decisions. In his work the pilot is assisted by the flight test conductor who is sitting in the control room and in permanent radio contact with the pilot. The flight test conductor is supported by the flight test engineers. They monitor important parameters on-line/real time in the control room and inform the flight test conductor.

After the test flight the post flight meeting is conducted to discuss problems encountered, objectives accomplished and requirements for the next flight.

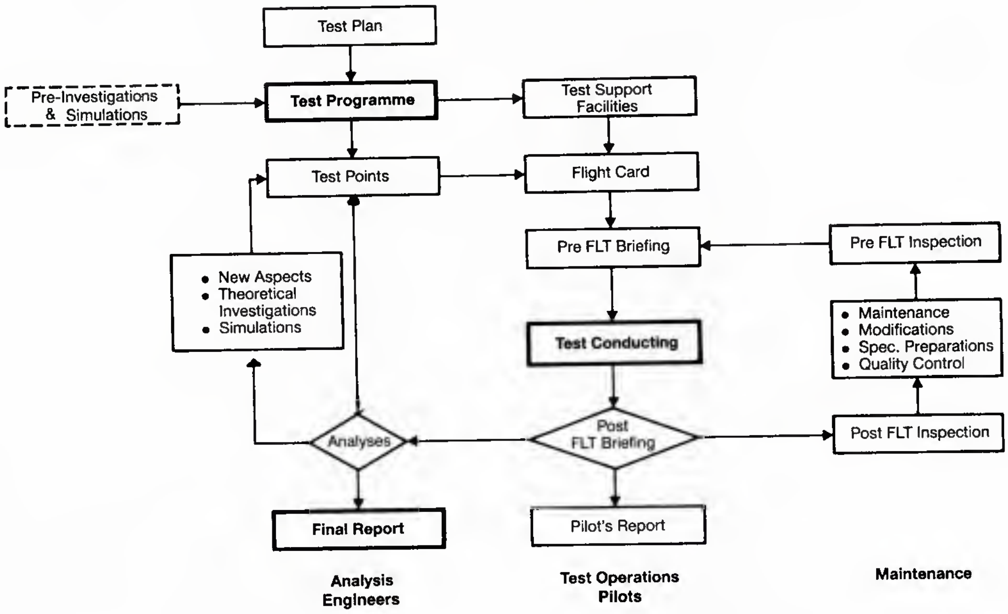

Fig. 8 - Sequential Course of Flight Trials

5.2 Characteristics of Fighter Aircraft Testing

Generally, flight testing, as the last stage of a complex system integration test process, must concentrate on two main aspects:

1) Investigation of individual systems and integration of all subsystems into a weapon delivery system under realistic flight conditions

2) Verification of the air vehicle behaviour and performance with the pilot-in-the-loop under mission oriented conditions.

Subsystem integration flight tests should be based on a bottom-up test architecture relative to the aircraft systems or system specification architecture including aircrew and mission aspects as shown in Fig. 9.

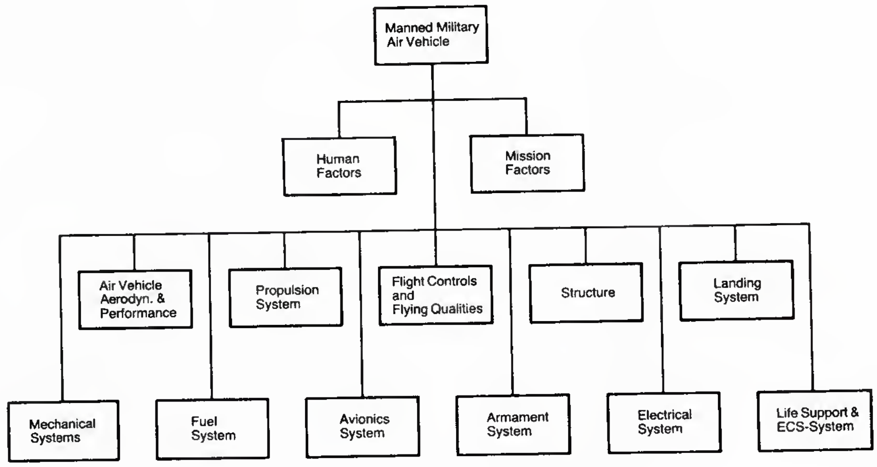

Fig. 9 - Test Architecture

In addition to that, for the fighter aircraft special features must be taken into account such as an extremely wide flight envelope (from 100 to 800 kts), a large variety of aircraft configurations and external stores (which create hundreds of combinations), a high degree of agility, and a large range of load factors. Mission profiles require operations at low levels (down to below 100 FT) and high speeds under all weather conditions but, also up to high altitudes above 50000 ft from low to high speeds.

Fig. 10 shows a typical flight envelope to be investigated during testing. Under extreme fighter mission conditions and combat manoeuvring the aircraft operates around its max. lift capability and close to the structural limits of the airframe. This means high demands on the aerodynamic quality of the airframe, the engine/intake compatibility, the

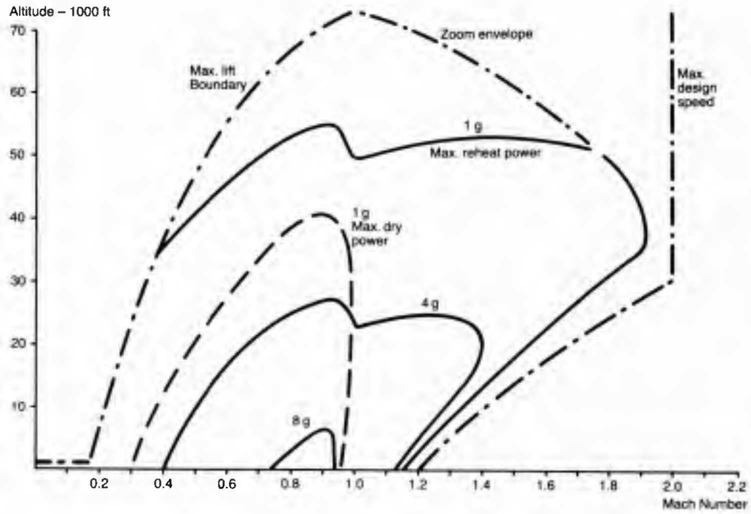

Fig. 10 – Typical Areas within a Flight Envelope for a Fighter Aircraft

stability augmentation, the control-, avionic-, and weapon systems. Natural instability and carefree handling are some of novel characteristics. All these became technically feasible with current technologies such as electronics, sensorics, computers, fly-by-wire, etc. But new interference factors, for example EMC problems, come more and more to light and must be taken into account. New trends like direct force, thrust vectoring, post stall, fuselage aiming make the system even more complex.

The implications of the pilot-in-the-loop under extreme operational conditions must carefully be investigated already during development and evaluation flight testing because the human factor can hardly be considered in the theoretical calculations. Necessary modifications to control laws and gains or aerodynamic improvements due to unacceptable buffet must be detected at the earliest stages of flight test.

Such an extensive field of flight test activities accumulate to quite a number of flight hours and time in order to achieve the test goals. A survey of the amount of flying, which is a basic cost factor for flight testing, is given in Fig. 11 for typical projects up to the achievement of an Initial Operational Clearance.

Experience shows that in the average about 5 to 10 flights per month and test vehicle could be achieved during such a test phase.

The need to reduce expensive and time consuming test flights to a minimum resulted in the development of dynamic test techniques, advanced data processing procedures, digital model matching and in the use of flight simulators.

Besides these, it becomes increasingly important that the very complex software and avionic/armament subsystems of a modern fighter are completely evaluated and tested at the component level before they are installed into the test vehicle, in order to avoid basic subsystem development or qualification tests during flight test.

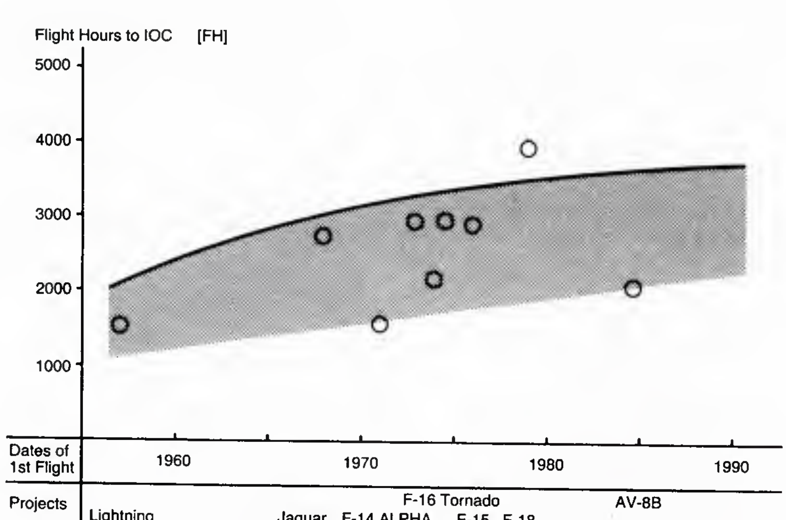

Fig. 11 – Trends in Flight Hours to Achieve IOC

This aspect carries additional weight due to the fact that the relevant integration trials of the avionic/armament system occupies an ever increasing part within a flight test program as illustrated in Fig. 12. It must be assumed that flight testing of these systems will claim about 50% of flight test expenditure in future already up to IOC.

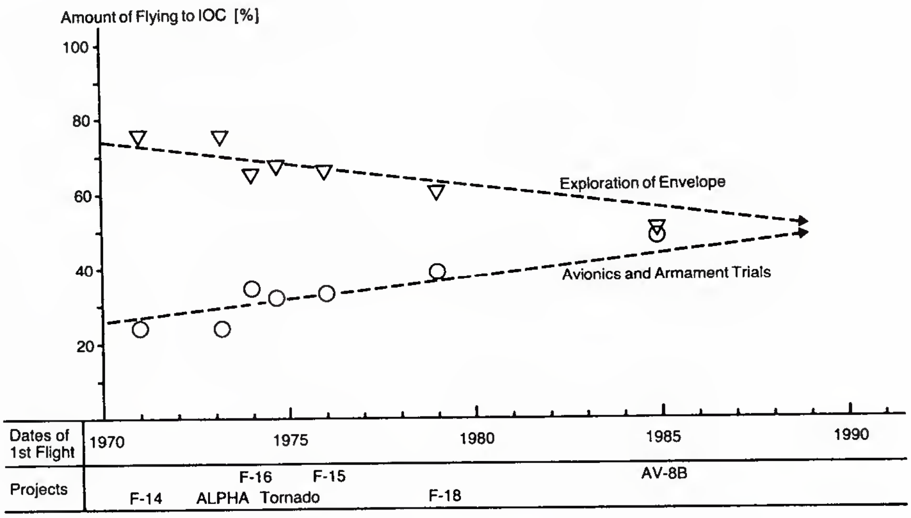

Fig. 12 - Trends in Flight Test Tasks Sharing to Achieve IOC

6. TEST DISCIPLINES AND TEST METHODS

As indicated in the previous chapters flight test is an universal discipline. In fact, this becomes obviously when regarding the large field of engineering disciplines as given in figure 13. This is only a summary of typical flight test tasks representative for a current fighter aircraft test programme. A detailed description of all these items would extremely expand the scope of this paper.

But some aspects should be regarded at least for the testing which is normally required before the test vehicle gets airborne for the first time and then for main flight test disciplines.

6.1 Basic Ground Test Prior Flight Test

Prior to fight testing each subsystem installed in the test vehicle will be ground tested in accordance with its system acceptance test procedure.
These tests will be performed in assistance with flight test system engineers and include basic systems like engines, hydraulics, electrics, communication, navigation, identification, controls and displays, electrical power, radar, store management, data processing (mission computer/multiplex bus control) and flight test instrumentation system tests.

Extensive flight safety electromagnetic compatibility (EMC-)tests are required prior to the first flight for each test vehicle or have to be repeated after changes or modifications of relevant subsystems.
Such tests become more and more important for a flight test program because the portion of electronics is rapidly increasing in modern flighter aircraft and these tests are characteristically as complex as the avionics/electronics system architecture are. Furthermore, specific test facilities (EMC test chamber, radio frequency environmental generator) to simulate the extended RF environment or test methods (bulk current injection-method) are required to determine the EMC characteristics and the hardening level for the aircraft. More details are given in Ref. 5.

As soon as the basic systems show satisfactory ground operations within the test vehicle taxi test will be conducted to investigate the ground roll characteristics to develope ground handling procedures for safe operations. Special attention will be paid on basic systems, handling, performance, aerodynamic effectiveness, structur, undercarriage, brakes, etc.

These trials will finally lead to the clearance for first flight of the test vehicle.

In the following a selection is made out of the various test methods, concentrating on some typical and advanced procedures, important for in-flight investigations of fighter aircraft.
General tendencies in flight test are:

- change over from steady state to dynamic manoeuvres
- use of model based analysis techniques to reduce the number of test points
- rigorous application of real time/on-line data processing and analysis

to save expensive flying time.

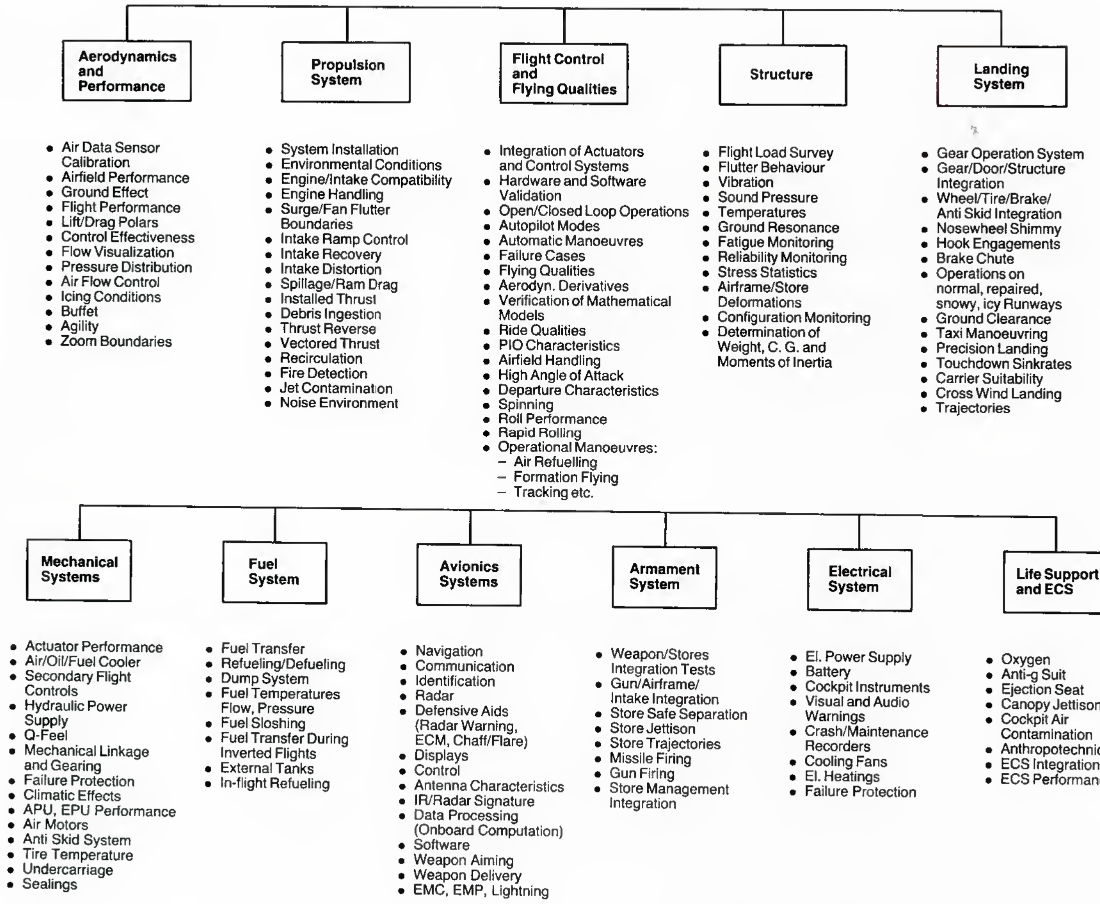

Fig. 13 - Flight Test Disciplines

6.2 In-Flight Thrust/Drag Determination

The standard procedure to evaluate the aircraft's performance is to measure specific parameters like specific range, climb and descent performance, turn rates, max. speed, specific excess power (S.E.P.), take-off and landing performance (distances, speeds). Data of those tasks can accurately be determined by in-flight measurement of appropriate performance parameters under test conditions.

Simplified methods to correct the obtained results to standard weight and ISA conditions are instructed at the established Test Pilot Schools in the USA and Europe (corresponding manuals about performance flight testing Ref. 6).

However, these correction methods usually assume a linear relationship which do not hold for an advanced aircraft. Satisfactory results are only obtained for small deviations from the standard conditions.

Another approach is a flight test philosophy that provides a full understanding of the aerodynamic quality of the airframe in terms of lift/drag polars and the performance of the engine throughout the flight envelope. The separation of thrust and drag is favourable for

- proof of compliance with guarantee aspects
- quick identification of aerodynamic problem areas on the airframe and on the engine including the intake
- identification of drag increments due to airframe modifications or due to external stores
- better optimization of airframe and engine
- utilization of flight test based polar/thrust data for the mathematical model for handbook calculations.

A further advantage is the independence of the polars from the engine performance standard.

This approach has been applied in the last decade in Europe and in the USA during flight testing of complex aircraft like the F14, Tornado and others.

Utilizing dynamic flight manoeuvres, this way has proven to be efficient and thus economic which is important for new fighter development programmes.

Appropriate thrust/drag evaluation methods and test techniques are available (see Fig. 14 and 15) and shall be discussed briefly. Details are given in Ref. 3 and 4.

Engine Performance

Despite being the most important factor, the installed net thrust cannot be measured directly in-flight. Instead of this it is calculated from in-flight measured engine and aircraft parameters. In summary the basic principle is as follows:

- Measurement of certain engine parameters like pressures, temperatures, fuel flows, airflow, thrust, nozzle area, r.p.m.'s and inlet conditions on the ground, preferable within an altitude test facility (ATF)
- measurement of same parameters (except thrust and airflow) during flight
- calculation of installed gross and net thrust, airflow, specific fuel consumption, (s.f.c) utilizing the flight measured data and the ATF-calibration curves.

The requirement to support the calibration curves by a sufficient amount of ATF test data is expensive but substantiated by the accuracy necessary for the evaluation of, for example, aircraft drag improvements. With this method it is possible to separate thrust and drag, since thrust-dependent intake and afterbody drag components can be determined.

For a customer test center, which is more interested in the expeditious testing of the flight performance of complete developed airplanes, the so-called MCA-Method (Ref. 7) for example which is based on the principle of conservation of energy - is a simple tool. There is no need of any engine calibration or engine instrumentation except for fuel flow and basic aircraft parameter measurements. Engine evaluation is not possible since the airflow, gross thrust and other characteristics cannot be calculated and only informations about the total parasite airframe drag can be derived.

Aircraft Drag/Lift Polars

For development testing several methods are available to establish the drag polars. Well-known is the method of "steady level flying", a time consuming approach, if applied alone (i.e. - method). But, S.L. are mandatory in combination with dynamic manoeuvres, which are time saving and thus advantageous manoeuvres regarding the quality of results achieved. Usually in a test flight the steady level is followed by a roller coaster with a subsequent wind up turn, thus producing data for a complete polar including the zero lift drag within minutes as illustrated in Fig. 15. Further suitable dynamic manoeuvres are accels, decels and 'Split'S'.

All these methods require a careful in-flight calibration of air data sensors (Ref. 8), the engines initially to be stabilized and the power lever unchanged during the complete manoeuvre. This is important during the recording of those parameters required to calculate a confident engine thrust.

With the above described methods any kind of polars for any configuration can be evaluated.

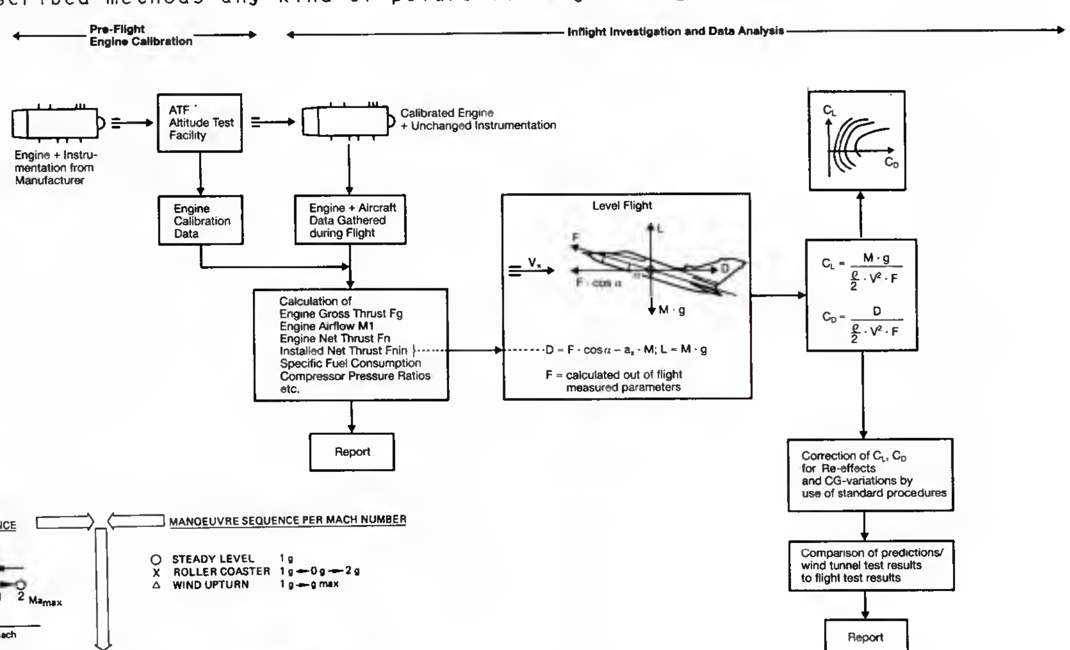

Fig. 14 - In-Flight Thrust / Drag Determination Method

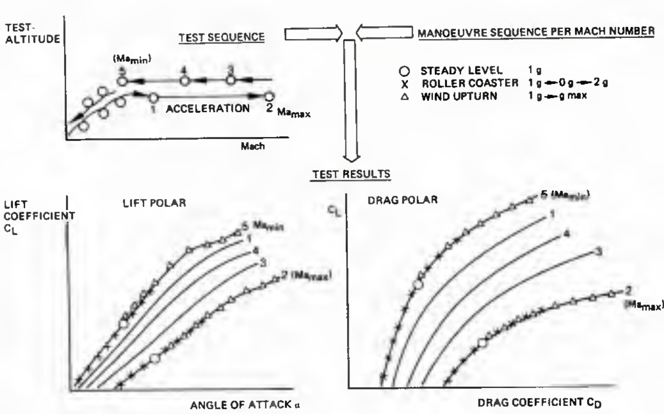

Fig. 15 - Test Technique for In-Flight Polar Measurement

6.3 Flutter Testing

The flexibility of the aircraft structure will always influence the aerodynamic behaviour of the aircraft in flight. Couplings of elastic forces with inertial and aerodynamic forces can lead to the well-known phenomenon of flutter.

The frequency responses of flight control systems in modern aircraft will increasingly extend into the frequency range of aircraft elastic modes which fact is enhancing the additional feedback loop for the flutter behaviour.

Due to the sophistication of the flutter mechanism in such modern aircraft with nonlinear elastomechanics and variable control systems, flutter clearance must be provided on a combined computer model analysis - and flight test verification base.

In this concept, the primary part of the clearance work must consist of calculations with the best available input data from structural modelling, ground resonance - and wind tunnel testing. Task of the flight test must be to verify the calculated results for updating of the mathematical model where necessary and the final demonstration of the flutter clearance in the entire envelope.

The "classical" method, to check the stability in the entire envelope by mode excitation, mechanical response measurement and subsequent damping - and frequency determination must therefore be extended to provide additional information relevant to the flutter mechanism. This will include measurements of the control path responses in all relevant control modes, measurements to identify sources of nonlinearities and to determine their characteristics.

The physical parameters, which have to be measured in-flight in order to identify the system will mainly consist of:

- accelerations (as means to determine displacements)
- internal structural forces (associated with oscillation modes)
- deflections and positions of control surfaces
- control system signals as gyro or accelerometer outputs or stick and pedal inputs
- basic flight parameters as speed, Mach, angle of attack and sideslip, load factor, etc.

Typical flutter instrumentation locations and excitation systems are shown in Fig. 16.

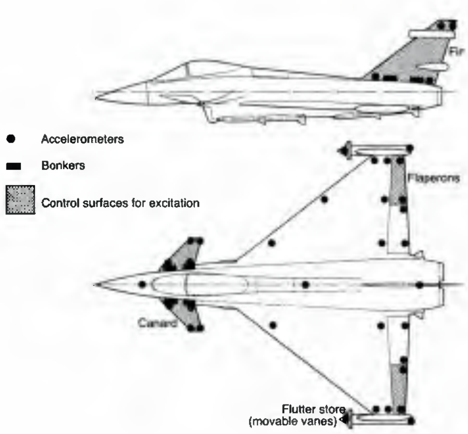

Fig. 16 - Typical Accelerometer Installation and In-Flight Excitation System

No.	Type	Advantages	Disadvantages
1	Nat. turbulence	No additive to the A/C	Low vibration level no transfer function available
2	Abrupt movement of control surfaces	as No 1	Excites only special modes
3	Bonker		Limited firing per flight sensitive to burning time additional mass
4	Inertia Load	Effective when in Resonance	Expensive in construction for larger A/C, additional mass
5	Vibration of control surface	as No. 4	as No 2 and danger of interference with A/C manoeuvrability
6	Additional aerodyn surface	as No. 4	Efficiency depending on dynamic pressure, additional mass

Fig. 17 - Possibilities for Flight Vibration Excitation

The methods for the system identification have and will further benefit from the availability of digital computer capacity and are:

- Power Spectral Density (PSD) analysis
- Transfer function analysis
- Modal analysis
- Filter correlation method
- Nonlinearity investigation.

On-line evaluation during the flight and on-line clearance to further test points should be an aim during the flutter test flights. Hereby the parameter identification process, applying the Maximum Likelihood and extended Kalman Filter procedures, are used for test data analysis. A typical application is described in Ref. 9. However, it should be kept in mind that even with the availability of the most modern on-line evaluation procedures and methods, structural nonlinearities, random signal disturbances and other unexpected efforts will limit an automated flight flutter test process in general. The updating of the analytical model with flight test results, the revised damping trend calculations thereafter, covering the aircraft in all control modes will also in the future require a careful step by step envelope extension. A conceptual overview of an advanced flutter test procedure is given in Fig. 18.

A key role in the parameter identification process plays an excitation of the aircraft with sufficient bandwidth with adequate level and the reliable knowledge of that excitation. Effort put into the excitation system pays in test time, data quality and increases the confidence into the results. In all cases harmonic excitations (sinusoidal or frequency sweep) must be preferred to random excitation, step inputs or impulse excitation.

The excitation signals can be transferred into the aircraft either through the control system or through driven aerodynamic vanes carried on the aircraft. Also inertial exciters have been used with success. Possibilities for flight-excitations are summarized in Fig. 17.

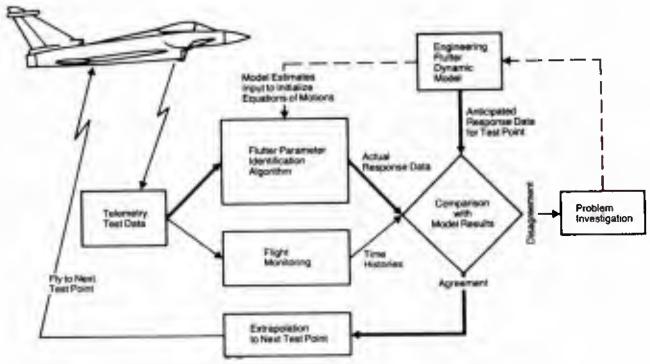

Fig. 18 - Advanced Flutter Test Method

6.4. Flying Qualities

In order to assure that no limitations on flight safety or on the capability to perform intended missions will result from the deficiencies in flying qualities, basic requirements have been defined in special specifications (i.g. MIL-F-8785, etc.). They provide means which enable the flight test engineer to assess quantitatively the stability and control behaviour of an aircraft. Additionally to this academic evaluation a qualitative assessment by the pilot, for example according to the Cooper Rating Scale, is considered to be essential to take into account human factors.

For these investigations the following pilot techniques have been developed:

- academic manoeuvres: doublets, pulses, wind up turns, steady heading sideslip, rolls. These can be regarded as the classical handling manoeuvres from which general flying qualities (GFQ), i.e. frequency, time constants and damping of the aircraft response but also stick force per g, neutral point, manoeuvre point and the specified derivatives can be derived

- operational manoeuvres: air-to-air tracking, air-to-ground tracking, close formation flying, inflight refueling, terrain following flying, weapon delivery, etc.
  With these types of mission oriented manoeuvres the pilot can rate (Cooper Rating) to what extent the required missions can be accomplished.

However, major problem areas in fight testing handling qualities of modern fighter aircraft with digital flight control systems (FCS) are the performance of closed loop tasks. Classical stability and control data analysis techniques have provided little insight into the understanding of the overall pilot-airframe-FCS interface because the advanced FCS can at times completely dominate the response of the airplane, resulting in a higher order system response. This comes to light when regarding the effects of the digital FCS dynamics (filter, time delay etc.) and bare airframe dynamic.

A suitable tool for analysing flight test data to provide a means to correlate FCS performance with pilot assigned handling quality ratings is the Parameter Identification (PID). The idea is to verify aerodynamic coefficients and the analytical model of the aircraft by a maximum likelyhood estimation.

One way is to use equivalent system models by reducing high order systems including the FCS dynamics to a low order system which finally results in Equivalent Derivativa! They can be estimated by the PID-technique using pilot control input instead of control surface as driving function. Thus frequency, damping and time delay can be calculated for the control and stability augmented aircraft (Ref. 10).

A more direct method to investigate high order systems is to measure the inflight total system frequency response to control inputs. The aircraft can be excited by an automatic input generator or by pilot inputs. Amplitude ratio and phase versus frequency can be evaluated using a time series, least square estimation technique. The results can be compared with modern handling quality criterias as defined in the frequency domain.
It is recommended to use different analysis methods and check against several criterias. But, after quantifying the handling qualities it is important to correlate the results with pilot assigned handling quality ratings to confirm established criterias, analysis techniques and to improve the characteristics of the aircraft when necessary (see Fig. 19).

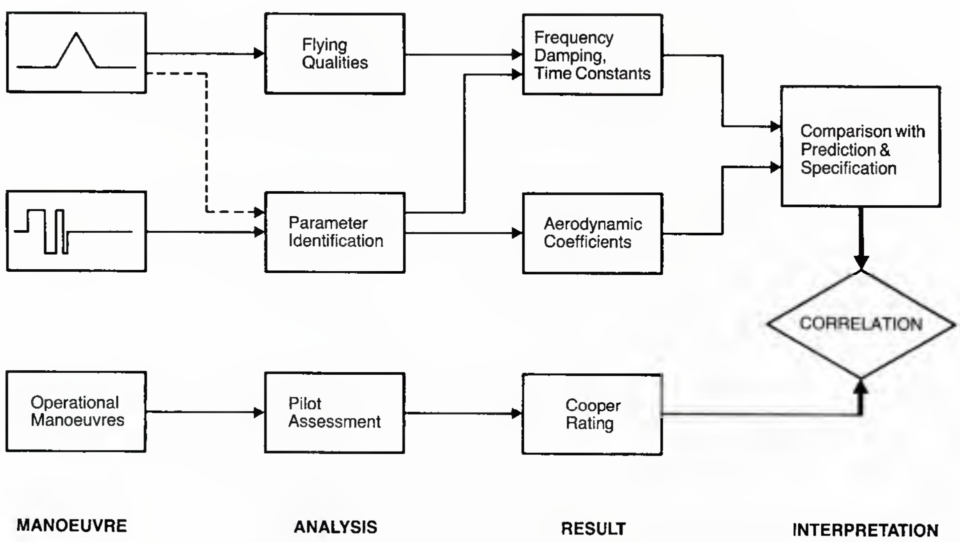

Fig. 19 - Analysis of Handling Qualities

6.5 Integrated Avionic Testing

Flight testing of avionics is normally characterized by testing the individual subsystems.
Classical avionics subsystem tests would include navigation, communication/identification, radar, airdata, data processing/mission computer, displays and defensive aids. Corresponding test disciplines are summarized in Fig. 13.
The starting point for the flight evaluation of most avionic subsystems are the system specifications which define system capabilities, accuracies and the verification requirements. In addition to that, testing is required to determine the functional adequacy or operational effectiveness of the total system, because subsystem capability may meet the specification requirements but may be operationally unsuitable.
This traditional basic test principle is still valid.

However, the capabilities of fighter aircraft avionic systems have expanded to a point, where traditional test techniques alone cannot fulfil present and future demands on flight test. Mission and flight performance requirements for a multi role fighter (night/low level navigation, terrain following, night/under weather weapon delivery, operation in increased threat environment, beyond visual range (BVR) engagement, extreme manoeuvrability, etc.) require the integration of a number of new systems. All of these additional features need to be integrated with other avionic systems utilizing several NATO-standard digital data buses, controlled by a mission computer. Fig. 21 illustrates an advanced avionic system architecture including new control systems, threat warning system, sensors, and weapons.
It is obvious that such a complex and high integrated avionic system with comprehensive interfaces will require improved or new test philosophies and test methods. The point of main test effort will be shifted to software development testing and to electromagnetic compatibility aspects.

Experiences show clearly that the higher level of integrated avionic systems resulted in a higher number of development problems reaching flight test.
The extended use of laboratory system integration test facilities combined with simulators is therefore state-of-the-art today in order to eliminate as much as possible avionic system design and mechanization problems on ground. A typical test process from design to flight test is illustrated in Fig. 20.
Such a procedure allows also flight test engineers and pilots to familiarize themselves with avionics system characteristics and avionics operating on the ground.
This comprehensive on-the-ground-testing saves time and money by concentrating actual flight time for final system integration testing under realistic dynamic flight/operational conditions.

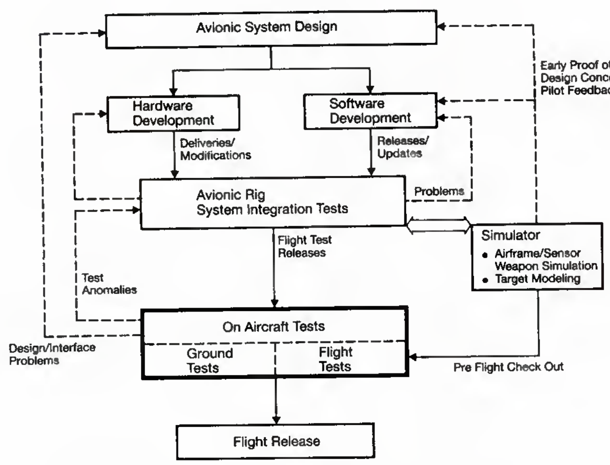

Fig. 20 - Avionics Test Process

The avionics architecture as shown in Fig. 21 is based around several multiplex bus systems as MIL-STD-1553/1553B. Such a standard bus allows up to 1 million bit/sec of data to be transmitted between up to 32 terminals.
Therefore, the avionics buses will be the must important data sources for avionic flight testing and analysis. An adequate avionics intrumentation system is shown in Fig. 5. But it should be kept in mind, that the recording of 100 percent of bus data needs an optimization of ground data processing in order to be able to handle this tremendous amount of data.

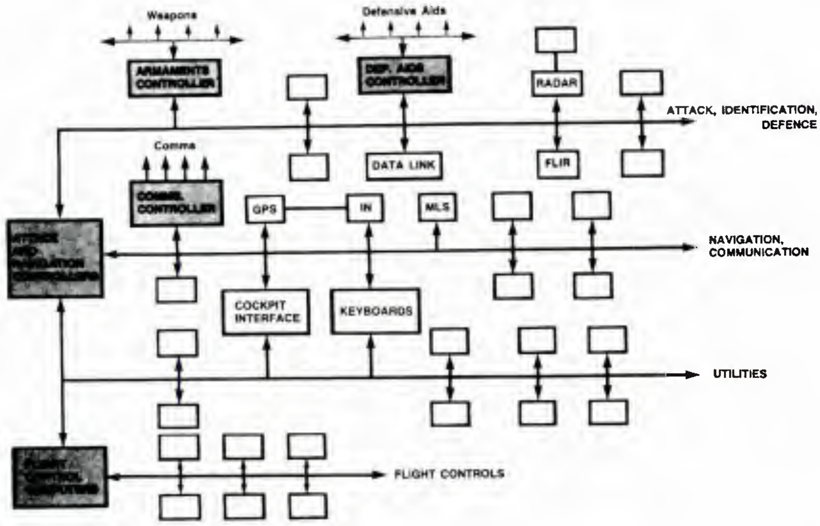

Fig. 21 - Integrated Avionics Architecture

Another important aspect is the video recording of complete cockpit displays, since modern fighters will extensively use the capabilities of multifunction displays, which are the pilot's primary interface for the control and display of sensors and weapons (see Fig. 22).
By recording these displays it is possible to determine the quality and accuracy of the sensors, the weapon video signals and to analyse pilot switch actions and the control status of the systems.
With these data sources, together with the use of real-time monitoring technique as described in section 4.2.2, it is possible to evaluate and analyse avionic system anomalies and to improve test efficiency by reducing the number of unsuccessful flights.

Due to the fact, that more and more aircraft systems are software driven, flight test will increasingly take place around software development testing and its associated problems.
Experiences gathered so far show that software testing is one of the most important test schedule driver.
Advanced fighter aircraft as F16, F18, Tornado are an example of a large scale software development effort. Within such test programs the originally planned software flight sorties had to be increased up to about 400 % in order to achieve software production release.
It is obvious that traditional test planning standards and conventional test methods must be changed and respectively improved.

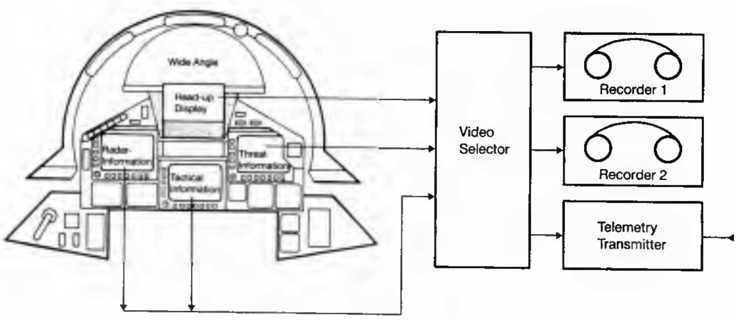

Fig. 22 - Cockpit Display of an Advanced Fighter Aircraft

An advanced test process as given in Fig. 20, should comprise the following main software test steps.

- o ground testing of software on a fully integrated hardware/software laboratory test facility **and** on the full scale test aircraft to realize basic development deficiencies as early and quickly as possible

- o performance of a pure software development flight test phase as a first step with the emphasis of finding and fixing problems (software verification by fly-fix-fly). The aim is to achieve faster a software standard which can be evaluated for production release during the next test step

- o software validation in flight to demonstrate that the software is in compliance with the specification.

Due to the complexity of avionics/electronics integrated in a fighter aircraft electromagnetic compatibility aspects are a particular and permanent task in flight test.
EMC investigations are usually functional in nature i.e. no quantitative onboard EMC-level measurements will be performed using specific instrumentation.
In-flight tests must prove the internal EMC of a fighter, that is the interferences between all ownship electronic equipments such as radios, threat warning systems (RWE, ECM) and associated antennas.
For example HF-transmitted power would be in the region of a hundred watts or more; that requires the investigation of effects on sensitive electronic equipments.
Also, the EMC of radar with all aircraft stores, especially ECM (electronic counter measurements) pods, have to be investigated.
In order to minimize interferences between radar and such systems, 'blanking' of signals are sometimes required. In this case radar and ECM pod performance degradation or loss of system effectiveness during 'blanking' have to be determined.
The effectiveness and the amount of external radiation sources (i.e. radio power stations, ground based radars) are increasing continuously all over the world. Hence, attention must be paid to investigate the effects of such sources on avionics and digital engine/flight control systems in particular. If any EMC problems are detected in flight, comprehensive ground tests in conjunction with specific test methods as mentioned in section 6.1 are required in order to identify the reasons and define means to solve the problem.

6.6 Weapon Trials

General objectives of weapon trials are:
to define system limitations for service operations; to identify factors affecting safety, useability and accuracy under operational aspects; to assess procedures for control of weapon delivery with associated symbology and displays; to determine overall system performance

Possible sources influencing overall system performance are:
ground checks and procedures for harmonisation, maintenance, etc.; sensor performance; computing system; operating conditions, procedures and system moding; in-flight deformations of the airframe; display and aiming; separation, balistics and weapon dispersion, etc.

All these facts can be determined and statistically analysed but, this gives little information about the system performance in circumstances in which any of the above factors are different. A more attractive approach has proven to be the use of Model Based Analysis. The intention is to fit flight test results to a mathematical model which is characterized by a number of quantifying constants or functions in such a way as to identify the values that apply to each attack mode (Fig. 23, Ref. 11).

Within this scope it is a complex aerodynamic task to take into account the disturbance of the aircraft; bow shocks with embedded subsonic regions; reciprocal shock interactions and reflections; unsteady motion of shock due to store motion after release; launch interference effects such as the jet interaction with the aircraft and store skin, etc.

These problems used to be solved by Potential Theory Methods with more or less simplifications. However, for modern fighter aircraft more advanced concepts like Zonal Decomposition (see Ref. 12) have been developed.

Thus it is possible to:
determine the flow field around the aircraft and stores, using the Panel Technique and wind tunnel data which are subject of improvement by flight test; calculate forces acting on the stores as a result of the aerodynamic flow field; calculate stores trajectories taking into account Ejection Release System Parameters (type of cartridges, throttle setting, position) and Stores Parameter (type of stores, physical characteristics, type of suspension system).

As soon as actual flight test measurements and calculations are in compliance we have a reliable tool to simulate each attack mode with realistic informations about the system performance.
For example Fig. 24 shows the calculated separation of an external tank by means of a flight test updated mathematical model.

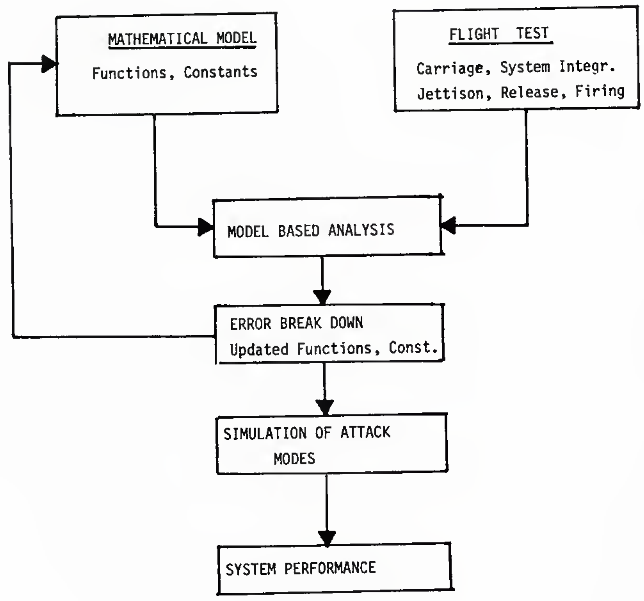

Fig. 23 - Model Based Analysis of Weapon Trials

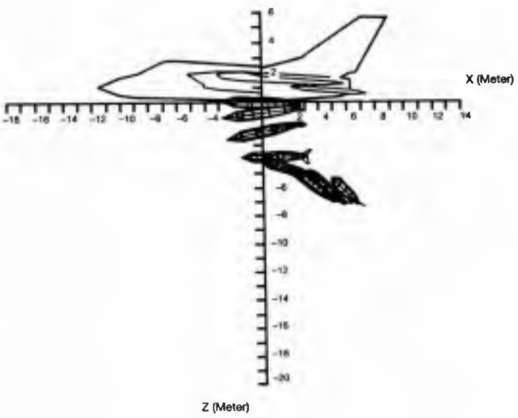

Fig. 24 - Flight Test Based Calculation of an External Tank Separation

The weapon trials destinguish Software-, Bombing-, Gun- and Missiles Tests.

(1) **Software Tests**
Modern fighter aircraft are equipped with programmable digital-multiplex control and display capabilities. In-flight investigations of the following software specific subjects are required: mission computers - store management processors - software management of the various computers - control, sequence and display under operational missions

(2) **Gunfiring Trials**
The development trials consist of investigating the effects of gun firing on: vibration levels at airframe and surrounding systems - engine operations - radar performance - night air-ground tracking - visibility due to gas particle accumulation on the wind shield, etc.
The final accuracy of gunfiring will be demonstrated under operational air to air and air to ground attack manoeuvres.

(3) **Bombing Trials**

The usual types of bombs to be tested with a fighter aircraft are:
general purpose bombs - free fall and retarded - guided bombs and dispensers.

The development flight test program starts with carriage trials. Subjects of investigations are:
effects on aircraft aerodynamics, handling, flutter, buffet, performance, etc. - determination of loads, sound pressure, vibration levels - airflow visualization.

Then the performance of delivery and determination of bombs patterns follows for the various modes, i.e.:
ripple single release at different time intervals - ripple single release as to required space intervals of ground impact - ripple single release from different preselected aircraft stations - releases at different dive angles - target designation by visual means, video, radar, laser, IR, etc. - manual and automatic releases and system specific modes, etc.
Fig. 25 demonstrates in-flight a full dispenser firing within 0.7 seconds.

(4) **Missile Tests**

Typical missiles to be tested on a fighter aircraft are air to ground-, air to air-, short range-, medium range-, long range-, and stand off missiles.

The development trials comprise carriage trials as above under (3) and

safe separation trials: to verify analytical investigations, to check engine operations and to investigate the effect of the jet and smoke plume on the aircraft

Then tactical shots are performed under various conditions as head-on; tail-on; look-down; look-up and manoeuvring (CAT 2, 3 trials, Fig. 26).

Fig. 25 - Full Dispenser Firing

Fig. 26 - Missile Firing

6.7 Operational Aspects

Within Evaluation and Development Flight Testing suitable manoeuvres are conducted to derive mainly specific derivatives of the aircraft. For this purpose the flight test engineer uses stabilized conditions or synthetic manoeuvres, the pilot has conducted in a precise way, to seperate interference effects as far as possible. As a result the flight test engineer can interprete the derived criteria in view of specifications (i.e. MIL Spec). However, with this set of manoeuvres the pilot is hardly in a position to rate the capability of the aircraft with respect to the mission requirements.

There are a number of subjects which cannot only be assessed by measuring quantities. Typical examples are shown in Fig. 27.

Consequently the pilot must be allowed to conduct operational mission profiles to get a realistic picture if the aircraft is suitable for the required service operations. Such aspects are also summarized in Fig. 27.

An adequate margin for pilot's errors in airmanship must be considered for the fighter pilot in service when he has to accomplish his mission and to compensate imponderabilities. In general for operational flight testing of fighter aircraft the tendency prevails of a 'Fly to Problem Concept'!

A typical example of mission oriented tests have been the evaluation of the terrain following system of the European fighter aircraft Tornado.
Safety and crew considerations were of paramount importance and the testing progressed in carefully controlled steps, beginning at 1500 ft set clearance height in visual meteorological conditions (VMC). The final clearance goal (FOC) of full automatic terrain following in instrument meteorological condition (IMC) at 200 ft height was achieved after approx 300 flights (see Ref. 13).

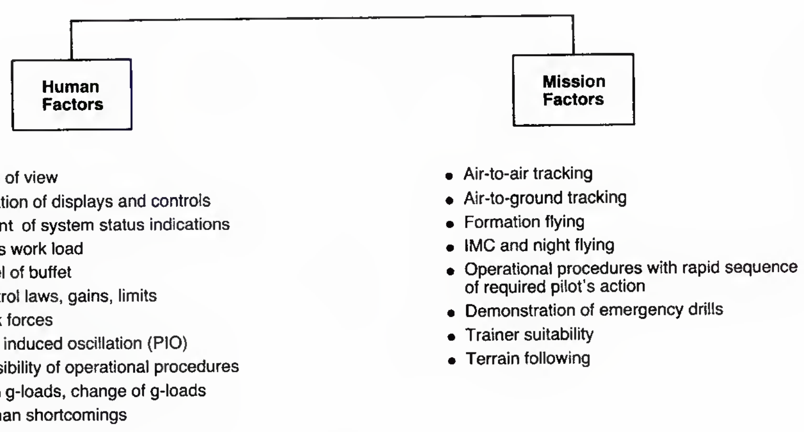

Fig. 27 - Operational Aspects

7. CONCLUSION

The concepts of advanced fighter aircraft result in decisive consequences for flight test. Complex systems, new materials, new technologies and increasing operational envelopes extend the field of flight test disciplines more and more. As consequence, the test philosophies and test methods have changed and have to be further developed and adapted to the next generation of fighter aircraft. But, limited budget and tight time schedules will remain. Hence, a flexible flight test organization, advanced test data processing, analysis and advanced test techniques become absolutely imperative to manage the clearance process of a modern fighter aircraft. No wonder that today's flight test engineer still appreciates with sympathy Otto Lilienthal's word when he summarized his experiences once in the following sense: "To invent a flying-machine means nothing, to build it does not mean much, to fly it means everything".

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CARRIAGE OF EXTERNAL STORES

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INTRODUCTION

In this lecture we will consider the main interactions between the external stores and fighter aircraft as a whole. Since our context is that of fighter design, we will concentrate on understanding the magnitude of those effects which can be chosen by designers.

The first part will deal with the factors that affect the overall value of a fighter airforce as a whole, so that we can appreciate the sensitivity of value to these factors. Then we will go on to consider the influence of the separate factors: Drag and other installed forces, Trajectory testing in wind tunnels, Stability and flutter, Agility, and Airframe/Store Integration. Thus the main sections are as follows:-

SECTION HEADINGS

* The "leverage" of store/airframe effects on air-force value
* Drag and other installed forces
* Trajectory: model testing
* Stability and flutter
* Agility
* Airframe/store integration

THE "LEVERAGE" OF STORE/AIRFRAME EFFECTS ON AIR-FORCE VALUE

Untill as recently as ten years ago, a loaded fighter tended to look something like figure 1. The airframe itself was smooth and carefully designed for low drag, but the stores and pylons often had excrescences more appropriate to a heavy truck. Why should the aerodynamic cleanliness stop at the pylon? I found that there was very little talking between store designers and aircraft designers, and just as little understanding of the effects of high-drag stores on the value of loaded aircraft and the airforce made up of those aircraft. The people who told the store designers what to do said that the stores had to be cheap, because they were to be used in large numbers. The idea that a dollar saved on a store by leaving an excrescence might increase the cost of the aircraft by a hundred dollars was not in evidence. So I started a campaign to work out what the costs and values of these interactions are, and to progress towards designs that would integrate store/airframe considerations into the design process from the start. This led to a major programme on store-drag reduction in the UK, and later to NATO-wide studies through the agency of AGARD (ref.1,2).

One of the main difficulties in the way of getting any improvements accepted into service was the language barrier between aerodynamicists and accountants. An aerodynamics engineer is happy to talk of drag coefficients and range, and even rate of turn, but the people who control the money tended to ask "How much does that cost, in dollars?". What is worse, they did not seem to understand at all clearly the vital distinction between cost and value. In order to clarify such matters, the following analysis was developed (ref.3,4). I hope that those of you who have seen it before will forgive the repetition.

Assessing the Value of an Airforce

Value is related to the amount that one would pay for for the usefulness supplied, in the circumstances of use. Thus the value of a parachute would change according to whether you have just fallen out of an aircraft, or you have dropped into the sea. Since the circumstances of eventual use are uncertain in advance, we have to postulate our best guess about a mixture of possible scenarios. The degree of uncertainty is well illustrated by the case of the Harrier, which was designed to destroy tanks in a central European environment, very close to bases, but it was actually used 13,000 km from home for ship-based air/air combat (in which they shot down 28 high-performance aircraft for no loss).

Simply to illustrate the concepts and the numbers involved, we will assume Close Air Support (CAS) operations in a short, sharp war,- at the end of which the opposition's airforce is out of action, while we have one aircraft left. In this scenario, replacement manufacture will play no part.

Factors of Effectiveness Value

The effectiveness, and therefore the value, of an airforce is proportional to the number of targets it can knock out before it is put out of action. It can be seen that this is proportional to a number of factors, which may (in varying circumstances) range between zero and unity. Let us examine these factors more closely.

Value $V \propto$ Effectiveness

Effectiveness $\propto$ Warload transport rate (unimpeded) (W)

$\propto$ Availability in wartime (including bases) (A)

$\propto$ Kill effectiveness (K)

whence V=WACK . . . . (1)

where C is the constant of proportionality.

We can see that if any one of these factors becomes zero, the overall value becomes zero,- no matter how marvellous all the other factors may be! Thus the enemy has plenty of scope to make our airforce useless and valueless.

Warload Transport Rate (W)

W = mass of ordnance transportable when unimpeded, relative to datum aircraft

= (ordnance load per sortie) X (number of sorties per day)

= m.N

Here the sortie rate (N) depends on:-

* turn-round time (r)
* block speed (M)
* distance from base to target area (d)

$$N = \frac{1}{r + 2d/M}$$

Therefore

$$W = \left(\frac{m}{r+2d/M}\right)_R = \left(\frac{Mm}{2d+rM}\right)_R \quad \ldots (2)$$

Where the suffix R indicates that the parameter is to be made "relative" by dividing by the comparable parameter for the datum aircraft.

It can be seen that a small aircraft capable of operating from bases near to the scene of the action may transport as much as a large aircraft that has to operate from far-back bases.

Availability in Wartime (A)

Availability = average fraction of aircraft time usable during war.

This depends on four factors:

* fraction of total time usable (t) { night-time capability; bad weather capability; availability of targets within range }
* fraction of aircraft usable (a) { agility, survivability; repairability; maintainability }
* fraction of bases usable (b) { runway length requirement; ground hardness requirement; base detectability/survivability }
* availability of stores (s) { logistics; interchangeability }

thus $A = (tabs)_R$ . . . . (3)

Thus the Availability term depends on many "ilities".

Target Killing Effectiveness (K)

K = specific rate of knocking out targets (per unit of ordnance released) relative to datum aircraft/store combination.

This depends on various aspects, but not generally in simple proportional laws:-

* power of weaponry

* active guidance of weaponry

* aiming accuracy of aircraft $\left\{\begin{array}{l}\text{aircraft controllability}\\ \text{sighting system}\\ \text{pilot's workload and battle fatigue}\end{array}\right.$

* accuracy of stores trajectory $\left\{\begin{array}{l}\text{ejector/carrier dynamics}\\ \text{aerodynamic release disturbance}\end{array}\right.$

The Constant of Proportionality (C)

If we arrange that all the factors of value are made non-dimensional by making them ratios, relative to the factors appropriate to the known datum aircraft, then the constant C amounts to the value of an airforce comprising a given number of the datum aircraft. That value is not set by engineers or accountants: it is set by political judgements. We can assume that the Government, in its collective wisdom, has decided that the value of the datum aircraft is not less than its lifetime cost. Then it follows that the constant C is not less than the lifetime cost of the datum airforce. For most comparisons, the value of C is not needed accurately, but it seems that typically it is around 5 times the cost of buying the aircraft (figure 2).

Nowadays, for an airforce of 100 CAS aircraft, the value of C must be in the region of $10 billion, so if we are able to increase any of the factors discussed by a mere 1%, the value of that small improvement would be about $100 million. We will see that substantially greater improvements can be made, for relatively very low costs.

Overall Value (V)

Substituting from (2) into (1) we get:-

$$V = C\left(\frac{Mm}{2d+rm}\right)_R (tabs)_R\, K_R \quad . . . . (4)$$

Effects of Stores

Now we can examine the terms in equation (4) to determine which of them may be affected by store/airframe interactions. Obviously the datum constant C is unaffected by our proposed improvements to store/airframe integration. In the transport rate factor (equation 2) the block speed or block Mach number (M) may be affected by store drag. The ordnance mass per sortie (m) also may be affected, for if the drag can be reduced substantially, ordnance may be exchanged for fuel. In the denominator, the average distance (d) from forward base to target is determined by the basing versatility (e.g. whether the aircraft is CTOL, STOL or STOVL) but not directly by the store installation. The turn-round time (r) depends clearly on the accessiblity and serviceability of the store installation.

In the availability term (which embraces many "ilities") there are four factors. The usable time factor (t) may be increased if reduced drag increases range enough to bring targets within range. The "aircraft usable" term (a) can be affected quite markedly, for reduced drag may increase both the penetration speed and the agility - both of which may reduce the attrition rate. The stores installation may affect the radar and infra-red signatures, repairability and maintainability aspects. The last two terms (b,s) will not concern us here, after remarking that there are strong arguments in favour of NATO-wide interchangeability of stores to make overall logistics more economical, and also there are good reasons to tighten up on certain dimensional and ERU cartridge tolerances.

The target knock-out term (K) obviously may be sensitive to the store installation, but numerical assessments may not be easy. If the stability and controllability of the aircraft are improved, clearly the pilot will be able to aim more accurately.

Even more important, if store trajectories are made more repeatable and accurate, fewer sorties will be needed. This latter topic will concern us in some depth. There are, incidentally, other possible effects of release disturbances. For example, there have been cases where the release disturbance disrupted missile "lock-on", and there have been many cases where jettisoned stores have flown about so wildly that they have struck the aircraft and caused severe damage or destruction of the aircraft.

To summarise; the terms of equation (4) which will concern us further are:-

* M block speed
* m mass of ordnance per sortie
* t target availability : effect of range
* a aircraft availablity : survivability - penetration, agility
* K target knock-out :stability, controllability, store trajectory

For the remaining relevant terms, note that it is important to ensure rapid turn-round, maintenance and repair. Store interchangeability needs NATO-wide attention. Radar and IR signature effects also need to be watched.

This section of the lecture has concluded that the value of an airforce may be increased sensitively by improving aspects of the store/airframe installation, in proportion to their effects on the factors of equation (4). The value of the improvements would normally be much greater than the costs involved, for each 1% improvement to a $10 billion airforce would be worth $100 million, while one may guess that the costs may typically be less than one-hundredth of that amount.

DRAG AND OTHER INSTALLED FORCES

The Significance of drag reductions

It can be shown (ref.5) that the generalised range equation can be approximated closely by the following equation:-

$$R = \frac{a_o}{(s/\sqrt{\theta})}\left(M\frac{L}{D}\right)\frac{F}{W_m} \quad . \; . \; . \; . \; . \; (5)$$

where a_o is the speed of sound at sea level, M is the cruise Mach number, (L/D) is the lift/drag ratio, F is the fuel consumed on this sector of the cruise, W_m is the logarithmic mean weight for this sector,and $(s\sqrt{\theta})$ is the jet engine specific fuel consumption generalised by the relative temperature of the atmosphere.

The significance of this form becomes evident when we note that the first term embraces the engine performance, the second embraces the aerodynamic efficiency, and the third expresses the fuel consumption in terms of the mean weight for the sector.

From equation (5) it is clear that if we double the drag of our aircraft while leaving the third term fixed, the range is halved. In practice, doubled drag would usually lead to reduced cruise Mach number, so the range would be reduced on this account as well. In addition, the extra cruising thrust would severely eat into thrust reserved for acceleration and manoeuvring, so the agility would be severely impaired.

Now let us examine what courses we may adopt if the clean aircraft drag were doubled by a draggy store array (noting that many store arrays have been far worse than this). From equation (5) we would have to double the fuel mass ratio (F/W_m) to restore the range. Ideally the extra fuel should be carried without altering the exterior size or shape of the aircraft, so we try to double the internal fuel tankage. That leads to more tank weight - by perhaps an extra 12% of stage weight, so now we have to add a further 12% of the total fuel, just to keep up with the extra weight of tankage. Already we are trying to carry 224% as much fuel as would be required by the clean aircraft, but we are not done yet, for the tanks get heavier and more costly as we try to cram them into smaller and more awkward corners. Probably we cannot get so much extra fuel into the original size of aircraft, so we have to increase its size, and weight, and the engine size. . . Perhaps this process is getting frustrating, and we should try to carry the extra fuel in external tankage? This does not help very sensitively, for tank drag is very high, and a substantial fraction of extra fuel will now be needed merely to propel the external fuel tanks. The tanks could be dropped when empty,- at a price - but the drag of their pylons remains. Next we find that the agility has become comparable to that of an old cow, so a bigger engine is needed,- but that would normally have a higher specific fuel consumption . . . So if we accept the drag penalty of a bad store array, we finish with larger aircraft. Since aircraft costs depend mainly on installed power and aircraft weight, the airforce purchase cost increases substantially, while the fuel costs much more than double.

Figure 3 shows the significance of a store-drag reduction exercise conducted 20 years ago. The block graph on the right hand side represents the drag of the entire clean aircraft, while the block on the left represents the drag of the original array of stores and pylons,- well above the aircraft drag. It can be seen that the reduction of drag from cleaning up and fairing excrescences on pylons and twin-store carriers was greater than the total drag of the clean wing plus the entire tail unit. The dotted line blocks show the potential store drag that may be be achievable by undertaking radical redesign of the store array. The drag reduction is equivalent to completely eliminating the drag of the clean aircraft. Even a 10% reduction of the original store drag was equivalent to eliminating the entire drag of the wing.

So we conclude that the unthinking store designs that can still be seen in service were capable of ruining all the care that went into the design of the clean aircraft. Even today, aircraft designers may still be instructed to allow for the carriage of old high-drag stores, seemingly on the grounds that "they are still on the shelves". The high-drag store "tail" is still capable of wagging the high-expense aircraft "dog".

The example we looked at was an old one, but its importance was that it led to a programme in the UK to find how to reduce store drags. Research has progressed to such an extent that it is now possible to design store arrays with less than a tenth as much drag. We will look more closely at the principles involved.

Drag Prediction and Reduction

It will be worthwhile to outline some of the main principles of store drag prediction and reduction next, in order to understand the reasons for proceeding towards tangential and conformal store carriage, which will be dealt with separately in a later section. These principles were reviewed in depth by Barry Haines in ref.6 (1977) and revised in ref.7, and the following brief outline leans on those reviews.

The conclusions of ref.7 make a useful starting point for this section:-

"1) With existing external store arrangements, the drag increments can be very large, e.g. larger than the drag of the clean aircraft without stores.

2) Research has already shown how major improvements could be achieved, many of the suggestions even being feasible on existing aircraft.

3) New multiple carriers and underfuselage arrays of stores should aim to exploit the concepts of tandem carriage and store stagger and should avoid very close lateral spacing of stores.

4) There should be further exploitation of the favourable interference possibilities from wing tip carriage of slender missiles.

5) On new projects, wing/underwing pylons should be designed together with the aim of alleviating adverse interference at low C_L and achieving some favourable interference on the flow breakdown at high C_L at moderate and high subsonic speeds.

6) For new aircraft, the complete configuration should be designed as an entity with due regard to its longitudinal distribution of cross-sectional area and with the stores mounted either in conformal packages or from conformal pallets."

In the passage quoted above, the term "conformal" was used to embrace both integrated forms of carriage (which will be referred to as "conformal" in this lecture) and also carriage of stores mounted tangential to the surface of the aircraft (which will be referred to as "tangential carriage" below).

Reviewing the principles (1) to (6) above it can be seen that we need to be able to predict the effects of multiple carriage of stores, whether carried in tandem, staggered, or in line abreast, and to take account of pylon length and the shape of the local surface of the aircraft. Also the effects of wing-tip carriage need to be calculable.

That list of interactions seems formidable, but we will see that useful predictions can be made for all of those effects. The approach adopted in the UK since 1977 (successively by Pugh, Sadler and Ross of RAE) has been semi-empirical, using extensive sets of experimental results to understand the aerodynamics but fitting empirical curves through the correlated results.

Originally a "drag index" approach had been tried, in which the installed drag was expected to be equal to the isolated drag multiplied by an installation, K_I :-

$$\Delta(D/q) = K_I (D/q)_{isolated} \quad . \ . \ . \ . \ . (7)$$

where K_I would vary with Mach number and depend on the store array. When dealing with an array of stores, an extra factor K_A was expected in order to take account of mutual interference:-

$$\Delta(D/q) = K_I K_A (D/q)_{isolated} \quad . \ . \ . \ . (8)$$

However, Dyer and Gallagher (in the USA) had soon found that multiplying the interference factors together did not work: additive factors worked better. The RAE team found that it was necessary to split the factors into two parts: K_i to deal with parasite drags (largely independent of Mach number) and K_w to allow for wave drag (depending mainly on area distribution and Mach number). Thus for example, when calculating the drag of an assembly of staggered side-by-side stores, the equation is of this form:-

$$K_A = \frac{K_{Ai}(D/q)_i + K_{Aw}(D/q)_w}{(D/q)_i + (D/q)_w} \quad \ldots\ldots (9)$$

where $(D/q)_i$ is the low-speed or "incompressible-flow" drag of a single store, $(D/q)_w$ is the increment with Mach number in the isolated store drag, K_{Ai} is the low-speed assembly factor, and K_{Aw} is an assembly factor on the Mach-dependent drag.

In general K_i is not equal to K_w, and both terms may depend on lateral spacing, stagger and shape of stores. Methods for predicting $(D/q)_i$ and $(D/q)_w$ are improving, but for best results wind-tunnel tests should be done at scales large enough to represent the detailed excrescences of the full-scale store with reasonable Reynolds number.

Figures 4 and 5 illustrate how factors such as K_{Ai} and K_{Aw} are presented in the RAE method. Figure 4 shows the variation of K_{Ai} with lateral spacing (y/d) for two side-by-side stores with no longitudinal stagger (y being the minimum spacing and d the diameter). The equation:-

$$K_{Ai} = 1 + \frac{0.42}{\exp(y/0.4d)}\left[\frac{\text{store length} - \text{stagger}}{\text{store length}}\right] \quad \ldots\ldots (10)$$

provides a reasonable representation of experiment for various stores and with test Mach numbers low enough to be regarded as "incompressible". The allowance for stagger is not very accurate, but it will often be good enough for the low-speed component of the assembly drag.

Figure 5 shows the variation of K_{Aw}(i.e. the wave drag part) with store stagger. The parameter N is regarded as the "effective number" of side-by-side stores. Because adjacent stores can shield any given store from the effects of stores further away in a row, it was intended to take N as 2 when there are 2 or more stores and no stagger, and not more than 3 when there 3 or more stores with stagger. However, it is not that simple, and some more general rules are being worked out.

Figure 6 shows a comparison between predicted and measured drag for two Mk.10 bombs in a staggered arrangement on a standard carrier. The difference between the two curves shows the effect of stagger.

The RAE method also includes allowance for tandem-carriage effects. The forward store leaves a wake with reduced dynamic pressure, depending on the drag of the upstream store. Also the downstream store effectively lies in a stream with reduced Mach number. Figure 7 shows a comparison between prediction and measurement for two stores on a tandem beam. Note the magnitude of the tandem-carriage effects.

For underfuselage store arrays, the installation factors are generally not above 1.3, and can be below 1.0 for small stores semi-submerged into the fuselage. For pylon-mounted underwing stores, however, estimation of K_I is much more significant and difficult. Values of K_I at high subsonic speeds can be high, and can vary greatly with the wing design. After considerable research, multiplicative factors were abandoned in favour of an equation of the form:-

$$(D/q)_I = K_{Ii}(D/q)_{Ai} + (D/q)_{Aw} + F_A\, C_{D,ew} \quad \ldots\ldots (11)$$

where K_{Ii} is the low-speed installation factor, $(D/q)_{Ai}$ and $(D/q)_{Aw}$ are respectively the low-speed and Mach-dependent drags of the store assembly when isolated from the aircraft, F_A is the frontal area of the assembly, and $C_{D,ew}$ is the "excess" interference drag derived as a function of wing (thickness/chord) and clean-wing drag-rise Mach number (M_D) through a relationship of the form:-

$$C_{D,ew} = f(t/c)\exp\left(1.76\,\frac{M - M_D}{1 - M_D}\right) \quad \ldots\ldots (12)$$

Wherever possible, one should use measured values for $(D/q)_{Ai}$ and $(D/q)_{Aw}$.

Figure 8 shows the variation of excess drag with excess Mach number for three different combat wing designs. The full-line curves are from equation (12), while the dotted curves are from experiment. Clearly the agreement is good. Note that reduced wing thickness benefits the drag rise in two ways: M_D is increased, and $C_{D,ew}$ for given $(M-M_D)$ reduces.

An important conclusion from the research on underwing stores is that the wing lower surface and pylons should be designed to reduce the peak velocities near the wing/pylon junctions. There is more to this than merely reducing the (thickness/chord) of the wing. Presumably in time the prediction method will introduce some features of the underwing velocity distribution.

So far in this section, we have seen the way that the drag of an array of stores varies with the arrangement of the stores and with the nature of the surface near which they are mounted, and the nature of drag prediction methods which can indicate the magnitude of these interferences. One of the most notable effects is that the excess wave drag is sensitive to the supervelocities under the wing where stores may be mounted. As might have been expected, stores mounted much closer than one diameter apart in-line-abreast give increased drag, while stores mounted staggered or particularly nose-to-tail reduce drag. Where possible, tangential carriage (using the boundary layer of the aircraft as a low-velocity blanket) reduces the drag. We will return to consider the design implications of these conclusions more closely in the final section of this lecture, but before that we will first look at methods for finding other installed forces, then at other effects on the loaded aircraft.

Installed Forces on Stores

There are three main reasons for wanting to know the aerodynamic forces on "installed" stores. Firstly and obviously the total installed force in flight must not be allowed to exceed the strength of the structure (including the ERU and the store casing). Here the total installed force includes the aerodynamic force plus the inertia force, plus any impressed force.

Secondly, the aerodynamic forces just before release are valuable pointers to the impulses that will act upon the store just after release: indeed, some release trajectory methods rely on the aerodynamic forces as the main predictor of the post-release impulse. In any case, any unduly large installed aerodynamic force is a warning of significant aerodynamic impulse just after release.

Thirdly, in our present context, we may choose to interpret the term "installed" to mean "held in place". Many of the methods that can be used to find the forces on a store held in place on the ERU can also be used to find the forces on a store momentarily "in place" on its trajectory. So these methods may be used for trajectory predictions as well.

Distinction Between Drag and Rearwards Force

So far, we have been content to regard "drag" as a force acting on the loaded aircraft in the down-wind direction. It is important, however, to note that it is not generally correct to assume that the drag caused by a store can be found by measuring the rearwards force acting upon that store.

Let us pause for a moment to consider the fundamental distinction between drag and a rearwards force. Consider figure 9, which shows an aircraft regarded as though it were in a wind tunnel, with the air-stream flowing past it. In principle, we could find the overall thrust-minus-drag by surveying the streamwise momentum of the airstream behind the aircraft, at section 2, where we would find a lot of the air unaffected by passage of the aircraft, but some air would have less streamwise momentum than originally, and some would have more (as indicated by the graph of relative streamwise momentum). All the reduced momentum can be regarded as caused by the overall drag, while the excess momentum is caused by overall thrust. Much of the reduction in momentum is caused by streamwise obstruction of the airstream, such by excrescences and skin friction. Some is caused by relatively widespread conversion of kinetic energy into heat (by shock waves) and some is due to streamwise flow being diverted into downwash and sidewash, by vortices. Thus drag is caused by anything which converts axial flow into turbulence, heat or swirling wake.

Now imagine an aircraft wing under which we will hang a bulky store. Naturally the excrescences and skin friction will produce their own wake and a corresponding rearwards force on the store, but its extra supervelocities may also cause the boundary layer on the wing under-surface and the pylon to thicken or separate (extra wing/pylon drag) and moreover they may increase the extent and strength and intensity of shock-waves over a wide area (extra wave drag). Further, the store may cause increased suctions under the wing, thus losing lift which has to be restored by extra incidence, and thus more lift-dependent drag. Thus much of the drag caused by a store may be reacted upon other parts of the aircraft.

Buoyancy forces are quite different from drag forces, for they are due to the static field of pressure acting normal to the surface of a body. Any aircraft has a pressure field all round it, such that a relatively small body immersed in that field will experience a buoyancy force in some direction, depending on the location, for example. In principle, there is no essential need for a drag to arise, so it is common to find that if the buoyancy force acting on the small body were acting forwards (for example) then there would be an equal and opposite buoyancy force acting upon the aircraft, so that the overall drag is little affected. A wing slat, for example, may experience a large force acting forwards, but this does not mean that it has negative drag!

This little section concludes that drag cannot be measured simply by the axial force on a store, and further that buoyancy forces can be substantial for stores immersed in the pressure field of an aircraft (particularly for trajectory predictions).

Predicting Forces and Moments

In general, there are two major parts to any force-prediction method for stores. Firstly, the field of velocities and pressures in the relevant region near an aircraft has to be found. Secondly, the effect of that flowfield upon the store has to be found.

It will not be appropriate here to go into detail on all the various methods for making these predictions: for details see references 2,4,8. An outline of the main conclusions should suffice.

1) Flowfield

At an early stage, flow-field calculations by the RAENEAR method may suffice for many purposes. This method started from Nielsen's NEAR method, and was developed for much quicker data input and better accuracy in certain respects by successive UK workers under the auspices of the RAE. It is usually fairly accurate up to M=0.9, but does not yet cope well with configurations with relatively large air intakes. This method also calculates the forces on simple stores at moderate incidences.

The US code PANAIR (ref.9) gives quite accurate flow-field information at both subsonic and supersonic speeds, subject to the limitations of linearised theory. If substantial non-linear effects arise, such as boundary layer separations or strong shock waves, errors may become significant, but work has been done to deal with the real shock-wave problem.

In the UK, the SPARV code (ref.10) has been developed to a well-tested and user-friendly state for subsonic calculations. Work is now in progress towards extending this method through the transonic regime and into supersonics by developing the Field Integral Method for it. Here also, inaccuracies may be encountered where large air intakes are close by the region concerned, for which development is still in progress. First order boundary layer effects can be included.

Euler methods are being developed vigorously in Germany, the USA and the UK. These relatively major computations are coming into use even for design work, but despite their elaborateness (as with all the other calculation methods discussed here) will become inaccurate or even plain wrong once the real flow-field incorporates strong viscous effects, such as boundary layer separations. Shock waves are dealt with, if not too strong.

None of the calculation methods discussed will give proper indication of certain effects such as separation or major thickening of boundary layers, strong shock waves and wakes from other bodies nearby (e.g. a previously jettisoned store). Then a wind tunnel model of adequate scale, with excrescences represented (and exhaust and air intake effects, if necessary) becomes necessary. Given such a model, a favourite technique is to provide a second "sting" support, for the model store (see figure 10) and survey the relevant region of the flow-field.

The more economical use of this second sting is to traverse a region of the flow-field through which all store trajectories are expected to pass, to find the flow velocities and pressures at all points. Then the conditions at all points on any given trajectory can be found by interpolation. One way of doing this is to use flow direction probes on the "store" sting, and another is to use a calibrated model store (see IFM) and infer from the forces on it what the flowfield directions are. This flow survey method is increasingly popular because the flow-field data can be obtained with relatively little wind-tunnel time and cost, and numerous computations can then be made as required.

Another way of using twin-sting rigs is to mount a model store upon the second sting and traverse it, point-by-point, along its calculated trajectory. This is not so straightforward as it may seem, for the model store is momentarily at rest in the flow-field at each point, so the forces and moments measured for the store are not appropriate to what would be experienced by a store moving rapidly across the flow-field. Usually, this error is remedied (so far as the estimates allow) by incorporating estimated corrections to the store forces. However, the process of estimating these corrections for store motion may not be easy, or even possible, in rare cases.

Twin-sting rigs are widely used and are particularly useful for missile launch trajectory work, despite the fact that the wind tunnel Mach number may be substantially different from the Mach number attained by the missile by the time it has got level with the nose of the aircraft (for example). There are limitations in some cases, such as those where the store sting leads to base drag errors, and cases where the store assumes such large angles to the airflow that the sting cannot move accordingly. Multiple-store releases also are not tackled. For such cases, free-drop techniques can be used, as discussed in the section on store trajectory testing.

2) Forces on the Store

Given the aircraft flow-field, we now have to find the forces acting upon the store at every point in its trajectory. Now in the general case, a store may assume any angle to the local flow, in the presence of significant pressure gradients. We may attempt this either by calculation or by experiment.

There is only one calculation method which takes account of all angles of store incidence together with buoyancy forces: that is the BAe NUFA program (ref.11). This regards the store as a fairly general missile and calculates the forces on body sections and wing-like surfaces from correlated extensive data. The program predicts non-linear forces as the incidences become great, which can be vital in some releases (see figure **11**). The program is currently being extended through the supersonic regime. Bodies of non-circular section are not included.

Other calculation methods calculate the forces on stores according to linear theories, which are adequate only so long as the store does not assume angles of more than (say) 30 degrees to the local flow. They include RAENEAR and SPARV (subsonic) and PANAIR (both subsonic and supersonic).

There is an ingenious experimental method known as IFM (ref.12) in which a calibrated store may be used to survey a model flow-field and thus deduce its flow angles or, reciprocally, flow angles may be used to infer store forces. Unfortunately this method suffers from the drawbacks that the calibrations apply only to low angles of flow, and no account is taken of buoyancy forces. However, use of the IFM technique for deducing the model flow-field rapidly may remain an asset.

Euler methods may calculate the store forces at the same time as the flow-field, including shock waves if not too strong, but strong viscous effects are not calculated.

In principle, Navier-Stokes computations could calculate entire aerodynamic problems, but although some codes are quite powerful, relatively little experience has been obtained with aeronautical problems, and there will be a long way to go before they are used regularly for design problems.

TRAJECTORY: MODEL TESTING

There are two broad categories of releases to contend with: firstly releases of stores which merely have to leave the aircraft without damaging it, and secondly releases of weapons which are intended to knock out a target. In both cases there has to be no damage to the aircraft, but in the second category there is the additional requirement that the store should not suffer undue disturbance upon release.

We have already considered how to ascertain the aerodynamic forces acting upon a store both in position on its carrier and in the various positions it passes through on its trajectory. For early assessments of stores that are likely to assume only small incidences, several computational methods may be adequate, but for more complex circumstances it is better to use partly experimental methods. There are, however, various cases where these methods cannot cope with the complexities of the releases concerned; such as multiple releases of submunitions at very small time intervals (ref.13) or release of a light and highly unstable empty dispenser pod (ref.14) or ripple releases of bombs.

For such cases, free-drop model techniques are the best choice, unless one is prepared to proceed by small steps through highly expensive flight release programmes. It has been stated that the wind-tunnel based programme of store release clearance for the A-7D saved over $16,000,000 at 1970 prices, relative to flight.

Free-Drop Model Techniques

Naturally, the earliest experimental techniques involved dropping model stores in wind tunnels. If the model store trajectory is to be similar to that expected for the full-scale trajectory, then the ratio of aerodynamic to gravitational acceleration must be the same for both:-

$$\left(\frac{F/m}{g}\right)_M = \left(\frac{F/m}{g}\right)_F \quad \therefore \left(\frac{\frac{\gamma}{2}\, p M^2 C_F S}{\sigma V g}\right)_M = \left(\frac{\frac{\gamma}{2}\, p M^2 C_F S}{\sigma V g}\right)_F \; \ldots\ldots (13)$$

where store area is denoted by S, ambient pressure by p, store volume is V and store density is σ.

Froude Scaling

Putting the model scale as $1/n$, so that area scales as $1/n^2$ and volume scales as $1/n^3$, taking gravity as the same, and assuming that the force coefficients will be the same, equation 13 reduces to:-

$$\left(\frac{pM^2}{\sigma}\right)_M n = \left(\frac{pM^2}{\sigma}\right)_F \; \ldots\ldots (14)$$

Writing U=aM, where a is the speed of sound, and $a \propto \sqrt{T}$ we get:-

$$\left(\frac{pU^2}{\sigma T}\right)_M n = \left(\frac{pU^2}{\sigma T}\right)_F \; \ldots\ldots (15)$$

If the speed scale is taken as $n^{-\frac{1}{2}}$, the scale for densities becomes:-

$$\frac{\sigma_M}{\sigma_F} = \frac{(P/T)_M}{(P/T)_F} \quad . \; . \; . \; . \; . \; . \; . \quad (16)$$

This form of scaling is ideal for tests where the Mach number of the free-stream flow is of little consequence, and it is used for low-speed trajectory work, including snow and ice build-up and ingestion of debris from the ground during take-off and landing. However, it is often necessary to have the Mach number of the airstream the same as for flight, and then the problem of relating the model to flight becomes more complicated.

Light Model Scaling

It has been shown (e.g. ref.8) that the technique known as "heavy model scaling" is based on false reasoning. Light model scaling aims to make all the relative velocities scaled correctly (though not without problems).

First it is chosen to set the wind tunnel Mach number equal to flight. We wish to achieve with the model store the correct values of relative Mach number between local airflow and the store. To ensure that, it is essential to have the model store reach full-scale values of perturbation velocity. Thus it is necessary to make the aerodynamically caused accelerations n times the full-scale accelerations. Ideally, we have to make the gravitational accelerations also n times full-scale (we will come to this problem shortly). Then all the relative Mach numbers would be correct, and we would be entitled to set $M_M = M_F$ in equation 13, and consequently $C_{FM} = C_{FF}$,then using geometrical scaling for areas and volumes gives:-

$$\left(\frac{p}{\sigma g}\right)_M n = \left(\frac{p}{\sigma g}\right)_F \quad . \; . \; . \; . \; . \quad (17)$$

Supposing for a minute that we have provided properly for the gravitational acceleration of the model store to be n times that of flight, then:-

$$\frac{\sigma_M}{\sigma_F} = \frac{p_M}{p_F} \quad . \; . \; . \; . \; . \; . \quad (18)$$

so that the density required for the model store is equal to full-scale density times the ratio of ambient pressures (wind tunnel/flight). It can be seen that this is not a very low density, especially if a high-pressure tunnel is used.

How to Deal With the Gravitational Acceleration

What goes wrong if the gravitational acceleration on the model store is too low? If one pauses to consider the purpose of store release testing, one soon notes that we expect more trouble from aerodynamically agile stores, which may tumble and fly about dangerously. It is the aerodynamic accelerations which are likely to cause trouble: after all, an extra downwards acceration on the store would be expected to remove it more rapidly from the aircraft flow-field, and therefore from the source of troublesome motions. What matters in this context is the length of time that the store lingers in the aircraft flow-field, and this is generally too long if the passive free-drop technique is used. If our experimental technique does not allow anything better, a calculated correction to the trajectory can be tried, which will "correct" the trajectory further below the aircraft.

It is worth noting that in France they note the lesson of equation 17, which shows that the effects of the gravity deficiency reduce as the model scale increases: so they test models of fairly large scale (e.g. 1/4) in their Modane wind tunnels.

Accelerated Light Model (AMR) Technique

We have already argued that the main purpose of getting the gravitational accelerations right is to have the store subjected to the aircraft flow-field for the right length of time. It can be shown (ref.15) that most of this effect can be corrected for by accelerating the model of the parent aircraft upwards at an acceleration of (n-1)g, and measuring all trajectory data relative to the aircraft (see figure 12). A small residual correction amounts to imparting an additional pitch rate to the model store at the moment of release, by adjusting the ejector force offset distance.

This technique has been validated against flight test results and other techniques for the Buccaneer, Tornado, Harrier and Hawk aircraft, including a particularly sensitive release of an unstable empty dispenser, which tumbled vigorously.

Note well that for such methods, quite elaborate computation may be entailed in order to work out the correct end-of-stroke velocity to impart to the store. This is because the ERU acts as a device to impart a certain amount of energy, and that energy may be expended partly in pushing the wing upwards, and also partly in working against aerodynamic forces, as well as imparting kinetic energy to the store.

Other Model Test Techniques

Eaton and Farhall (ref.13) described an impressive wind-tunnel simulation of a rapid ripple discharge of tumbling multiple submunitions, with 3ms intervals between rounds.

In France, model releases have extended to include release of rocket-propelled missiles in wind tunnels.

STABILITY AND FLUTTER

Stability

Few systematic relationships have been noted for the effects of stores on stability, but the following (based on a survey by Coursimault, ref.16) summarises what is known.

Lateral Stability

Pylon-mounted external stores under the fuselage may reduce the directional stability and also lead to excessive sideslips in abrupt rolls: see figure 13. Stores mounted on conventional multiple racks under an F-4 fuselage caused more loss of lateral stability than tangential carriage. Wing/pylon stores may reduce lateral stability, but the effects can be kept within bounds.

Too little generalised work has been done to permit firm rules, but it can be speculated that part of the lateral effects are due to "forward fin" aerodynamics, and part is due to thick, low-energy wakes shed behind draggy underfuselage stores. Such wakes make the tail fin ineffective, and also tend to make the fin "wag" from side-to-side through the wake.

From such arguments one can postulate two rules:
1) minimise any tendency of the store to behave like a forward-mounted fin;
2) minimise the drag of underfuselage stores.

Longitudinal Stability

Generally, wing-mounted stores reduce the pitching stability, as shown in figure 14. Taissere (ref.17) concluded from comparisons of tests with and without tailplane that most of the stability loss arose from extra downwash at the tailplane. Stores alone (no pylon in position!) cause changes in the neutral point of the aircraft, but no change in downwash. Pylons experience increasing outwards lift as the aircraft incidence increases, and this leaves a trailing vortex wake which gives increasing downwash inboard of the pylon. A conventional tailplane would react to this with increasing download (unstable). When stores are added to the pylon, the outwards lifting force on this combination is greater, so the downwash in the usual tailplane position is increased.

These contributions depend, of course, on the relative heights of stores and tailplane, and so vary with incidence. They also vary with the amount of lift acting outwards on the pylon-store combination, so if the pylon were angled to have low lift, the tailplane-reacted downwash effect would presumably be reduced. It has been found that it is beneficial to reduce the sideways-facing area of the pylon, particularly under the wing leading edge, where the outwash is greatest. Tails on the stores may reduce the instability contribution, but this is mostly due to the reduced downwash at the tailplane.

Flutter and Unsteady Pressures

The main effects on flutter of wing-mounted stores are due to the effects of inertia, rather than unsteady aerodynamic forces on the stores. The extra inertia, together with extra degrees of freedom (such as pylon yaw elasticity, for example) introduces more vibration modes, and causes the frequencies of all modes to be lower. This creates many more opportunities for (say) a bending mode to nearly coincide with a torsional mode, and thus permit flutter. Each new degree of freedom introduces more opportunities for mode frequencies to coincide, such as fore-and-aft wing motion on pivoted wings, or rigid-body pitching on forward-swept wing configurations, or pylon/wing flexibilities. Wingtip store carriage, in particular, may entail the need for substantial mass ballasting to change a mode shape or frequency.

The numerous store types, in combination with a great variety of store stations, leads to an enormous number of possible combinations to check out. Since each computation is laborious, the aeroelastics specialists are always seeking ways to reduce the number of cases to be computed. It has been shown that clean-wing modes alone are not enough to give good flutter predictions: a combination of wing/flap modes, wing/discrete load modes and wing/pylon modes gives far better representation.

In some cases, the flutter speed is sensitive to store C.G, to pylon stiffness, or pylon frequency. It is not always simply a matter of increasing the stiffnesses, for the tuning required aims to prevent coincidence of (say) torsion and bending frequencies. For example, a low flutter speed may occur when the frequency for a bending mode is in the vicinity of a wing mode having considerable torsional motion induced by inertia loads

Unsteady aerodynamic pressures, which comprise in-phase and out-of-phase components of the pressures, are obtained by specialist codes such as NASTRAN or NLR doublet-lattice codes. Both subsonic and supersonic codes are used widely, but little has been published on transonic codes, though some work has been done using TSP theory. Nothing has been published on codes to deal with unsteady pressures arising from boundary layer separations.

Since the main basis for prediction, prevention and control of flutter is generally regarded as a corroborated mathematical/analytical model, and some elements of the aerodynamic modelling are not yet demonstrated to be adequate, there is usually a call for aeroelastic model testing to back up the computations.

Buffet Effects

Not all oscillating loads are due to aeroelastic phenomena, for an important class of loading actions arises from unsteady boundary layer separations; either over a large fraction of a lifting surface as buffet, or over a local region where local buffeting may arise (perhaps triggered by shock-induced boundary layer separation). One case was quoted where buffeting caused oscillating flap loads of ± 70% of the design load at 50 Hertz. For example, a large underwing store may lead to separation from a pylon/wing junction, which may soon consume the fatigue life of an aileron rod or flap hinge. Such effects are not amenable to calculation yet, and it is not routine to look for them. It is recommended that separations should be sought out (e.g. using oil-flow visualisation) and the local oscillating pressures probed with a transducer. The cost of finding and treating such local problems in the wind tunnel will be far less than the cost of a crash, or even modifications in service.

AGILITY AND PERFORMANCE

The effects of stores on aircraft agility obviously vary greatly with role of the aircraft (through the stores carried) and the particular missions flown. In order to assess the penalties of excessive store drag, and conversely the benefits of reducing store drag, it is necessary to calculate the performance of an aircraft with two different standards of store drag. An instructive study of this kind was made by Dr J Barche (ref.18). Since we are concentrating on high-performance fighters, we will examine the results he produced for an Air Superiority (AS) example.

Figures 15,16 show typical graphs of store drag versus Mach number. The stores of fig.15 are often carried on supersonic aircraft, but those of fig.16 are rarely so carried. Figure 17 shows a typical mission profile, in terms of altitude versus radius from base.

For his example, Barche took an aircraft of 30,000 lb MTOW and a thrust/weight ratio of 1.3 at take off, and considered the following external stores:-

* 3x 250 gallon fuel tanks, at fuselage and inner pylon stations,
* 2x Air/air MRM at outer pylons,
* 2x Air/air SRM at wing tips.

Working from the clean-aircraft drags appropriate to the various parts of the mission, together with the store drags shown, he calculated the ratios of store drag to clean-aircraft drag as shown in figure 18. These figures show that the store drags often range from 40% to 80% of the clean-aircraft drag. This diagram does not illustrate all of the penalties of store drag, such as the significant fuel weight penalties that may arise from relatively small extra drags sustained for large fractions of the time.

Performance Penalties

A concise indication of drag penalties may be seen by examining the effects on a few parameters, such as:-

* specific excess power
* steady state load factors
* specific range
* maximum speed

Other information such as rate of turn, acceleration and climb rate can be obtained easily from these.

Figure 19 shows a typical altitude versus Mach number plot of the SEP (=P_s) for both stores-off and stores-on. The first diagram is for level flight, while the second is for maximum manoeuvre. In both cases, the fuel tanks have been dropped already. As the SEP is defined by the equation:-

$$P_s = V(T-D)/W = w + V n_x \quad \ldots\ldots (19)$$

the flight envelope is given by $P_s = 0$ and $n_z = 1$. By examining the graphs it is seen that the climb or acceleration potential of this high-thrust/weight aircraft is not critically worsened by store drag, but the penalties are rapidly increased in the transonic and supersonic speed range. Therefore any reductions of high-speed drag considerably improve the performance in the transonic and supersonic speed ranges.

The effects on load factor are shown in figure 20, from which it can be seen that the penalties are of similar magnitude to those shown for SEP. Similar conclusions apply to Turn Rate, which is proportional to load factor at constant speed.
Specific Range effects are shown on figure 21. This shows that for subsonic/transonic flight, the losses of specific range are about 30% to 50% with all stores on, and still 10% to 15% with the tanks dropped. For supersonic speeds, the losses are in the region of 30% (tanks off and missiles on).

Thus even for this high-performance fighter example, without ground attack stores, the penalties due to the drag and weight of external stores were substantial. However, that study of 10 years ago was able to finish with a pointer to much less draggy means of carriage, by showing data from the F-4 tangential carriage demonstration, which we will consider shortly.

Sensitivity to Improvements

Barche's paper gave a concise presentation of an approximate analysis of the sensitivity of performance to store effects (also shown in refs. 4,19). However, a more direct presentation of the formulae is given below:-

$$\frac{\Delta r}{r} = -(4C_o-3)\frac{\Delta M}{M} + 2(C_o-1)\frac{\Delta W}{W} + 2(C_o-1)\frac{\Delta n_z}{n_z} - C_o\frac{\Delta C_{Do}}{C_{Do}} \quad \ldots\ldots\ldots (20)$$

$$\frac{\Delta P_s}{P_s} = -(4C_oC_1-2C_1-1)\frac{\Delta M}{M} - (1-2C_oC_1+2C_1)\frac{\Delta W}{W} + (1+C_1)\frac{\Delta T}{T} - 2C_1(C_o-C_1)\frac{\Delta C_{Do}}{C_{Do}} \quad \ldots (21)$$

$$\frac{\Delta n_z}{n_z} = -\frac{(1-2C_o)}{(C_o-1)}\frac{\Delta M}{M} - \frac{\Delta W}{W} - \frac{1}{2(C_o-1)}\frac{\Delta T}{T} + \frac{C_o}{2(C_o-1)}\frac{\Delta C_{Do}}{C_{Do}} \quad \ldots\ldots (22)$$

$$\frac{\Delta \omega}{\omega} = -\frac{\Delta M}{M} - \frac{\Delta n_z}{n_z} \quad \ldots\ldots\ldots\ldots (23)$$

$$\text{where } \left.\begin{aligned} C_o &= \frac{C_{Do}}{C_D} \\ C_1 &= \frac{V.D}{WP_s} \end{aligned}\right\} \quad \ldots\ldots (24)$$

Tangential Carriage

Jim Nichols' pioneering work led to the demonstration of the F-4 with tangential carriage of external stores (ref.20,21). The benefits of this mode of carriage are shown in figures 22,23.

Specific range effects are shown in figure 22, where the left-hand part shows the differences for low altitude flight, and the right-hand side shows the effects for high-altitude cruise. It can be seen that when the F-4 is fitted with empty TER/MER/TER racks, the range was reduced by 11% in cruise and 18% at low altitude. Adding 12 "low-drag" Mk.82 bombs, the range degradation came to 20% in cruise and 31% at low altitude. Alternatively, when fitted with an unloaded tangential adaptor, the F-4 actually had 4% more range at low altitude, because it covered over a draggy recess. When loaded with the 12 bombs, the range penalty was only 7% for cruise (instead of 20%) and 8% (instead of 31%) for low altitude flight.

The effects on the flight envelope were quite radical, as shown in figure 23. Note that with conventional carriage the aircraft had no supersonic capability at all: indeed the Buccaneer subsonic bomber then outperforms the F-4. With tangential carriage, however, the great majority of the supersonic flight envelope remains available. If the tangential carriage adaptor had been designed into the aircraft at the outset, instead of as a "boiler plate" retro-fit, the benefits would have been significantly greater.

Further work on tangential carriage has confirmed the benefits. Clearly large drag reductions can be achieved by mounting stores touching the surface of the fuselage and consequently partly immersed in its relatively thick boundary layer. The next question to arise was how much more benefit might be achieved by going further in this direction; for example by providing fairings around the arrays, or by semi-submergence, or by making specially-shaped stores to fit snugly to the surface. These questions are addressed in the next section, on "conformal carriage" or "store integration".

AIRFRAME/STORE INTEGRATION

The pioneering for this line of development was seen on the F-15, with its "Fastpack" (ref.22). Figures 24,25,26 show the versatility of the earliest version of this concept, which combines fast role changes and fast replenishment with low drag (figure 27). Bear in mind that the drag penalty of conventional tanks is commonly so large that a substantial fraction of the fuel is wasted merely propelling the tanks. In this case, the excess drag shown by the top curve would require perhaps 3,000 litres of fuel per hour merely to propel the tank at a Mach number of 0.9 at sea level.

Some of the newer work is classified, so we can only remark here that both semi-submergence and flat-top stores show substantial promise of drag reductions.

We may conclude that tangential carriage has been demonstrated as a practical way of achieving large drag reductions on suitable flat-bottomed aircraft, and there is a great deal of promise from pursuing this line of development further, towards store/airframe integration. Each scheme brings its own benefits and its own problems, which will have to be evaluated in the context of logistics cost and airforce value.

It is worthwhile to return to the analysis with which this lecture started. I hope that those who had seen it before have forgiven the repetition, on the grounds that it helps all of us to evaluate any changes which bring in a mixture of benefits (e.g. less drag) and disbenefits (e.g. worse logistics). Finally, it enables us to point out to those who hold the purse strings that the factors of VALUE are a totally different concept from COST. In this author's experience, it is usual to find that the increased value stemming from applying aeronautical research outstrips the cost over one hundred-fold. In other words: most of the time, each dollar spent on applying aero research brings over 100 dollars worth of better value to the airforce (or airlines). The real waste is to let a valuable piece of knowledge lie mouldering unused, perhaps until the opposition thinks of the same advance, and applies it.

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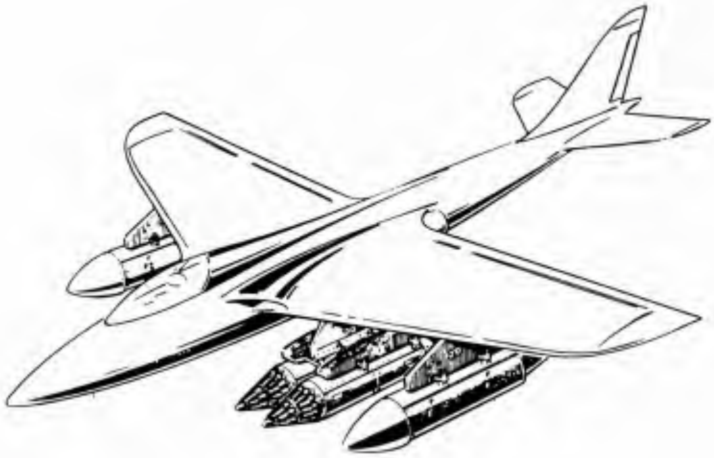


FIGURE 1 WHY SHOULD AERODYNAMIC CLEANLINESS STOP AT THE PYLON?

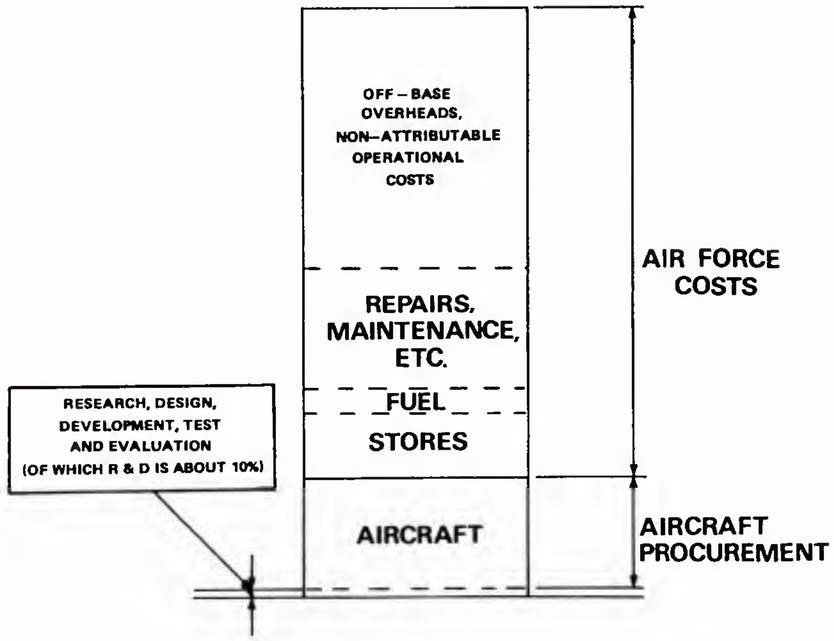


FIGURE 2 APPROXIMATE LIFE–CYCLE COSTS OF C.A.S AIRFORCE

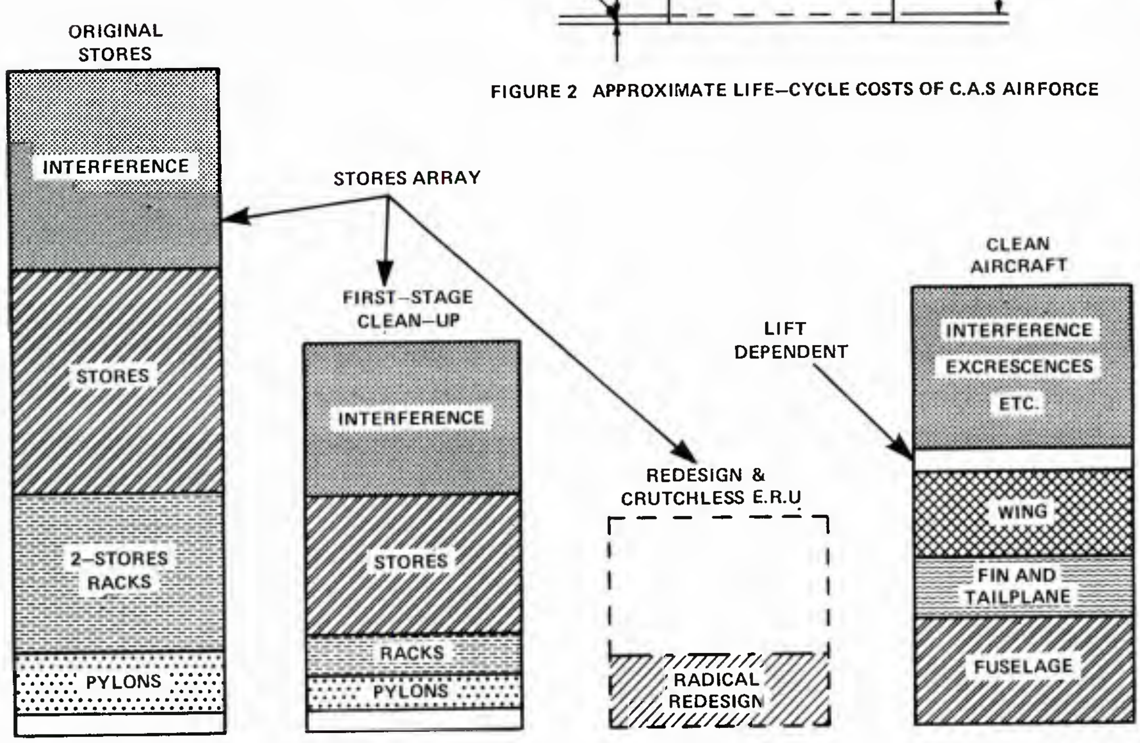


FIGURE 3 DRAG OF STORE ARRAY, AND CLEAN AIRCRAFT

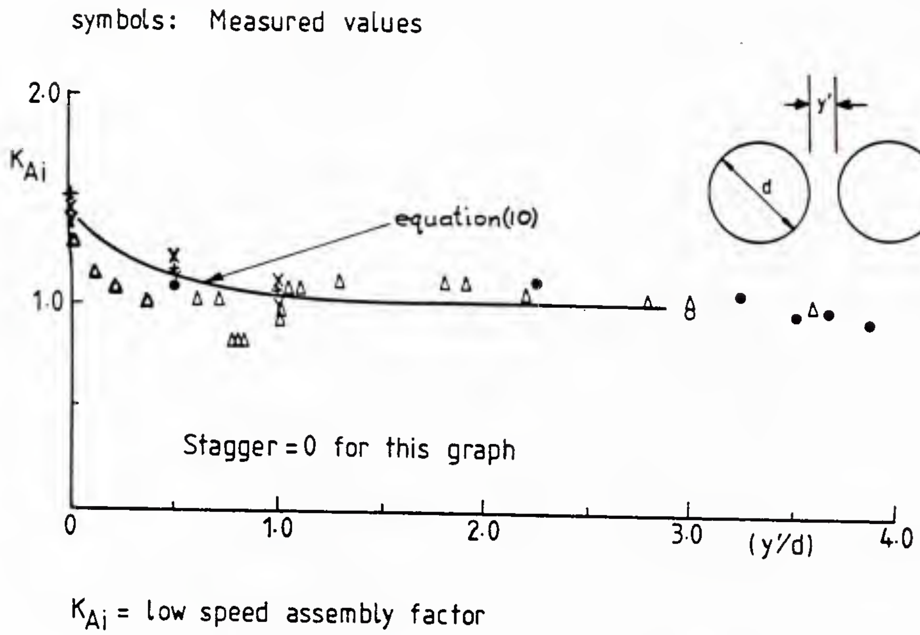


FIGURE 4 ASSEMBLY FACTOR FOR PAIRS OF SIDE–BY–SIDE STORES AT LOW MACH NUMBER

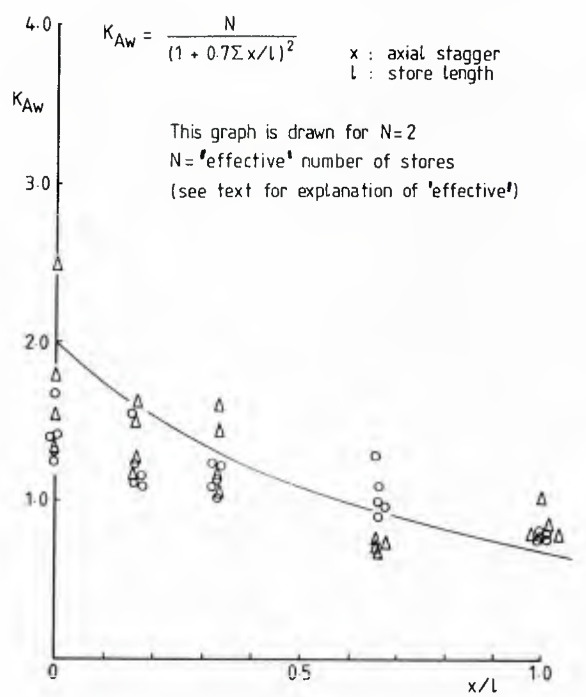


FIGURE 5. EFFECT OF AXIAL STAGGER ON HIGH SPEED ASSEMBLY FACTOR

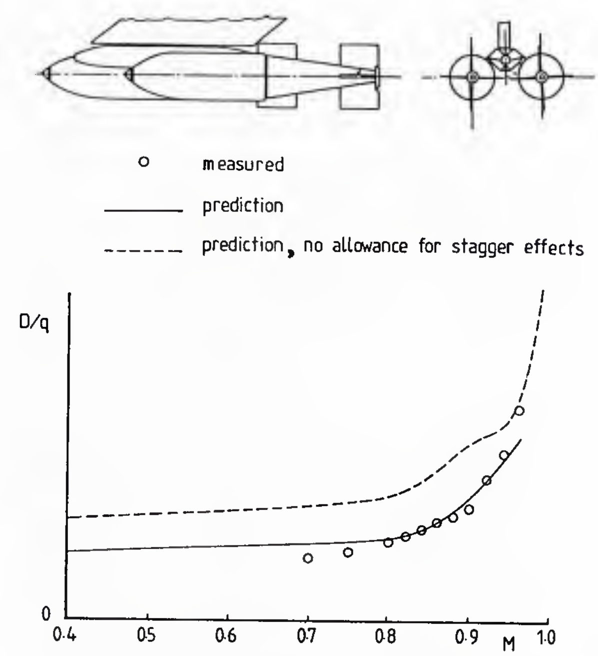


FIGURE 6 2 BOMBS ON A STAGGERED TWIN CARRIER

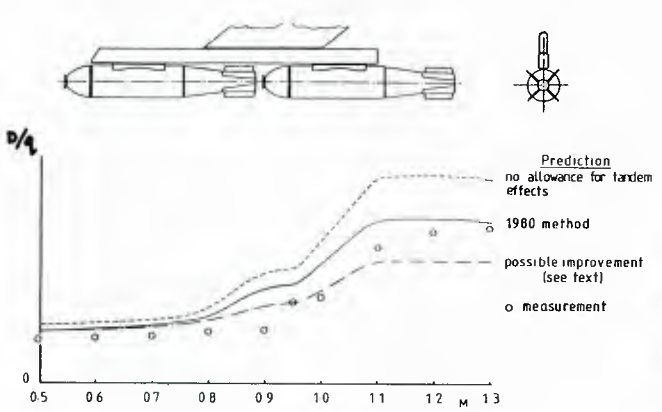


FIGURE 7 TANDEM MOUNTING OF 2 BOMBS

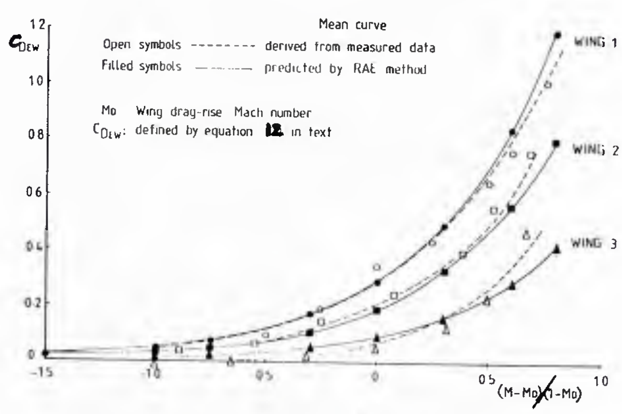


FIGURE 8 CORRELATION OF EXCESS WAVE DRAG WITH WING MD PYLON – MOUNTED UNDERWING INSTALLATIONS

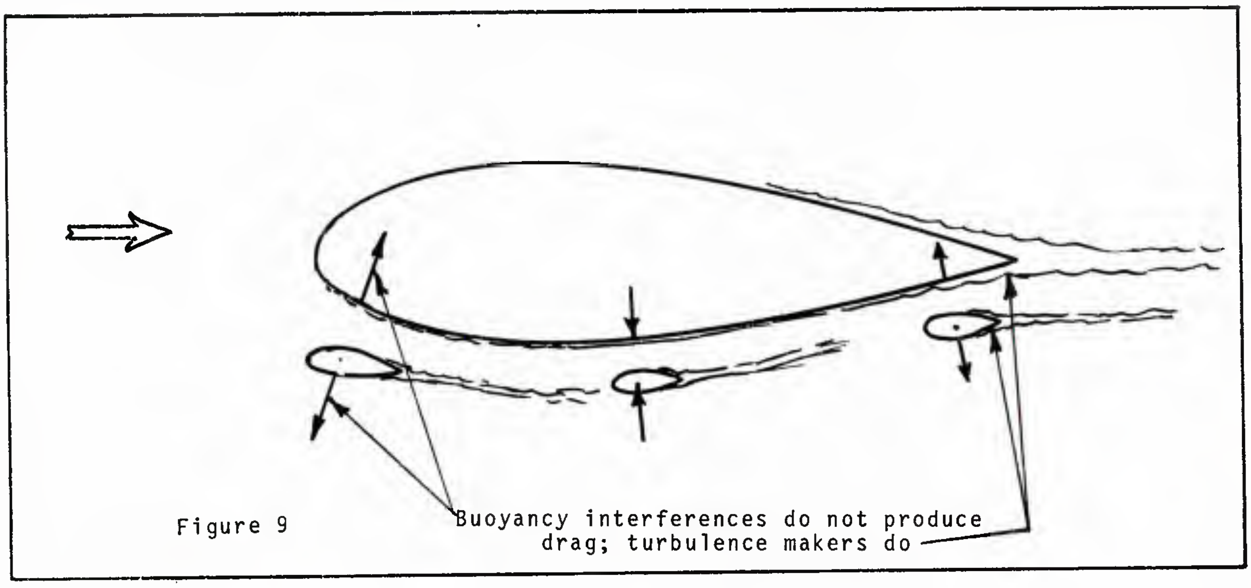


Figure 9

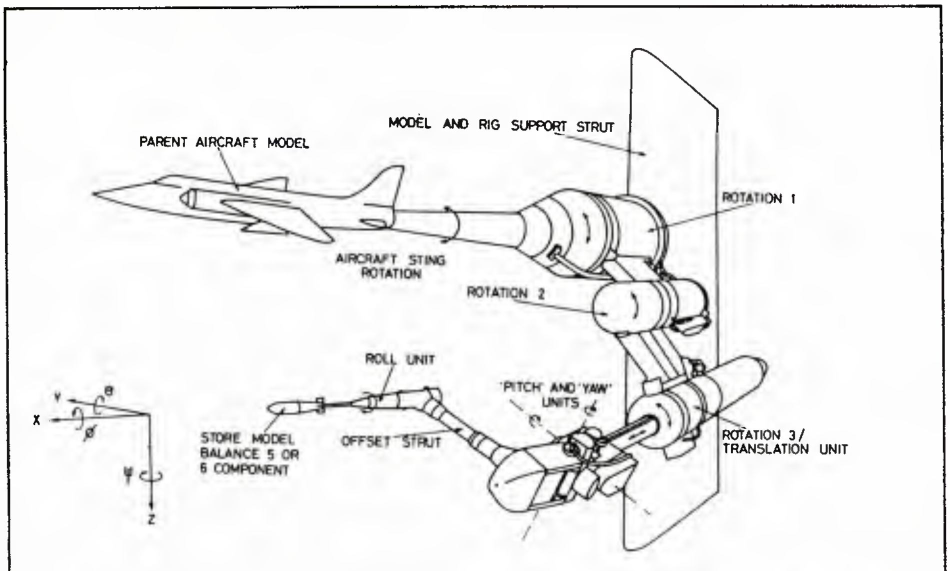


FIGURE 10 2-STING RIG *by courtesy of ARA*

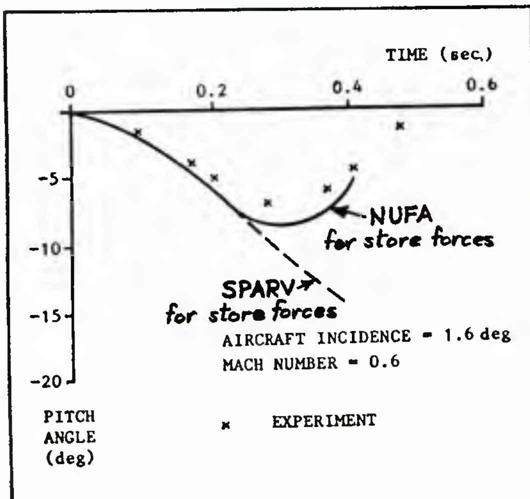


FIGURE 11 PREDICTION OF BOMB RELEASE PITCHING MOTION

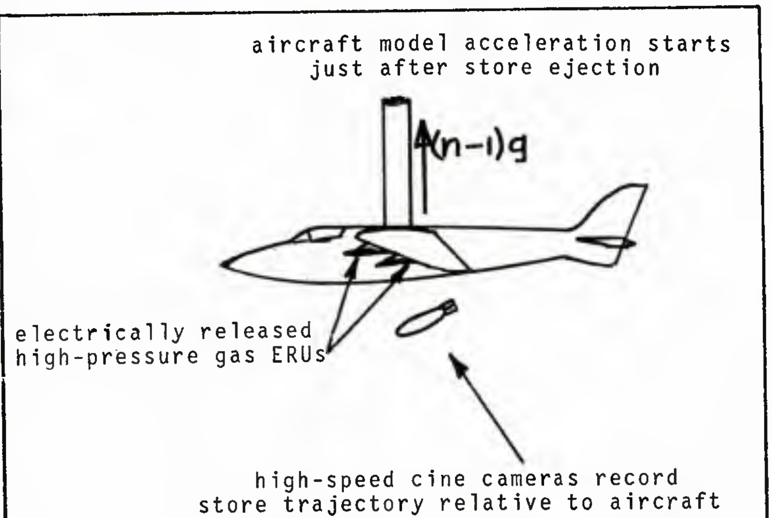


Figure 12 ACCELERATED MODEL RIG (BAe Brough)

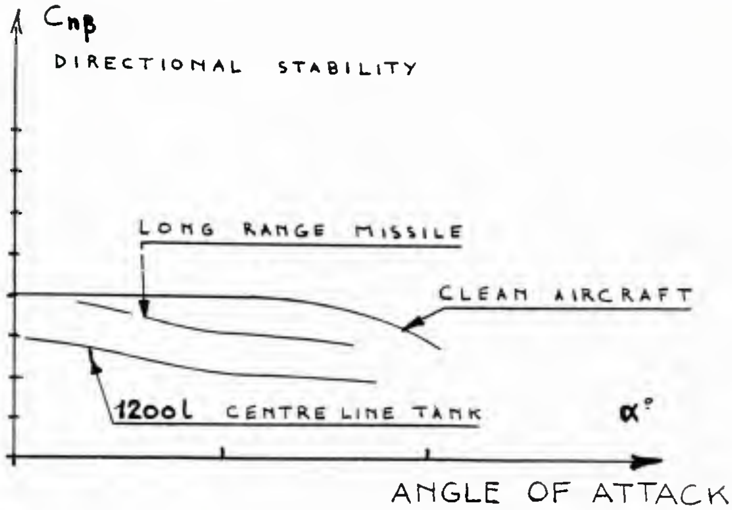


Fig. 13 INFLUENCE OF FUSELAGE STORES ON DIRECTIONAL STABILITY

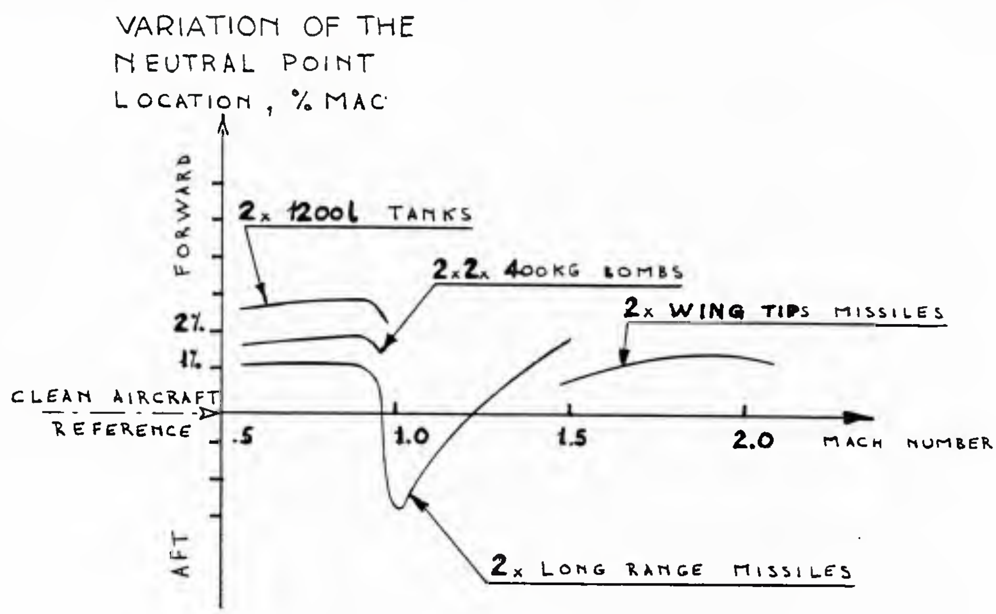
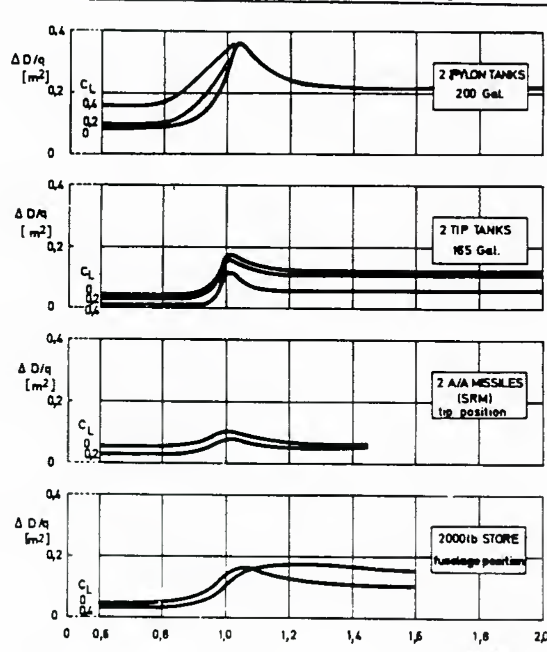


Fig. 14 INFLUENCE OF WING STORES ON NEUTRAL POINT LOCATION



INSTALLED DRAG of typical stores ①

Fig. 15

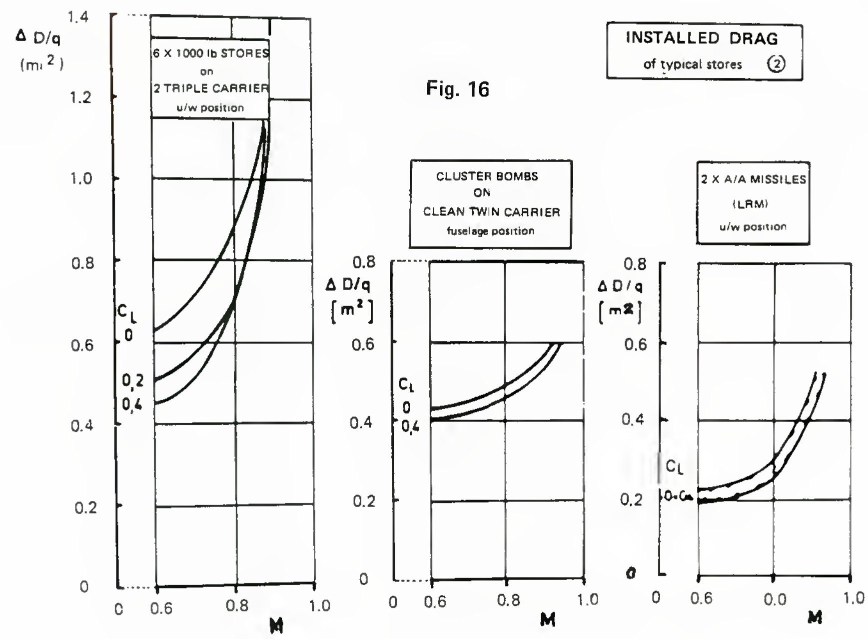
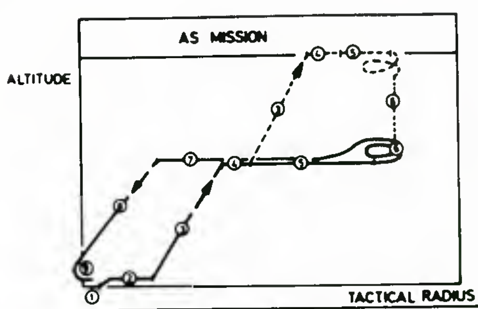


Fig. 16



AS - MISSION PROFILE				
No	Flight Phase	Altitude (ft)	Mach number	Time (min)
1	TAXIING, TAKE-OFF	0	0 - 0.2	3.0
2	ACCELERATION I	0	0.2 - 0.9	0.3
3	CLIMB I	0 - 18.000	0.9	0.5
3'	CLIMB II	18.000 - 36.000	1.2 - 1.4	1
4	ACCELERATION II	18 000	0.95	0
4'	ACCELERATION III	36.000	1.4 - 2.0+	1
5	CRUISE I	18.000	0.95	5
5'	CRUISE II	36 000	2+	3
6	COMBAT	10 000 - 36.000	0.6 - 1.2	5
7	CRUISE III		0.8	10
8	DESCENT	18.000 - 0	0.5	2
9	LANDING	0	0.2	1

Fig. 17

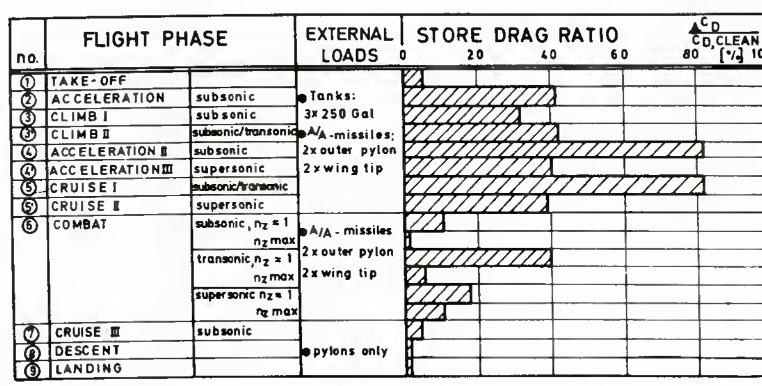


Fig. 18

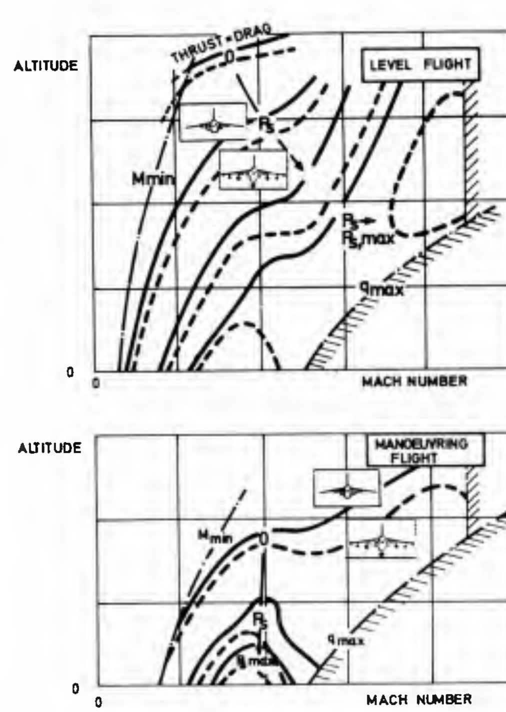


Fig. 19

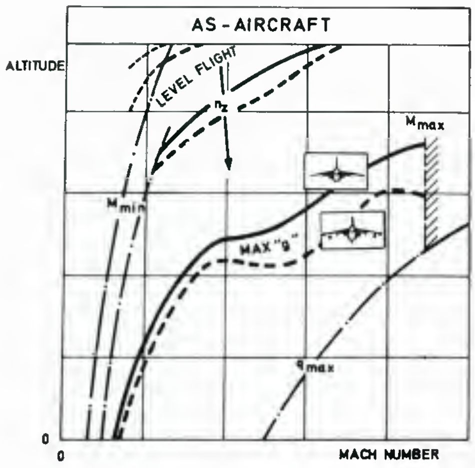


Fig. 20

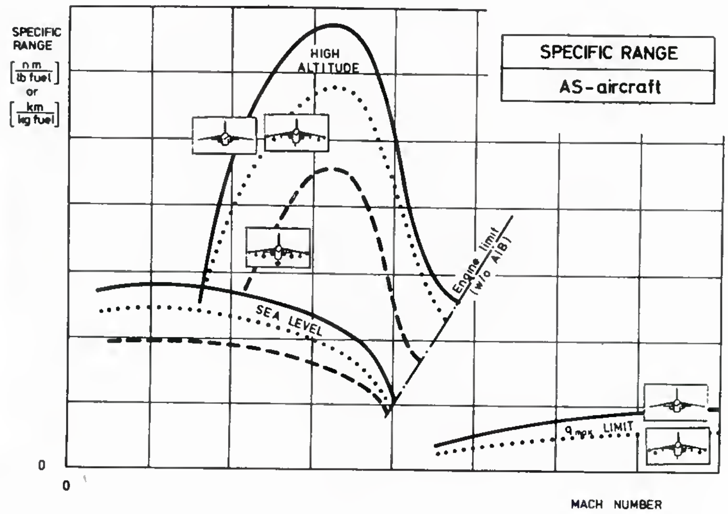


Fig. 21

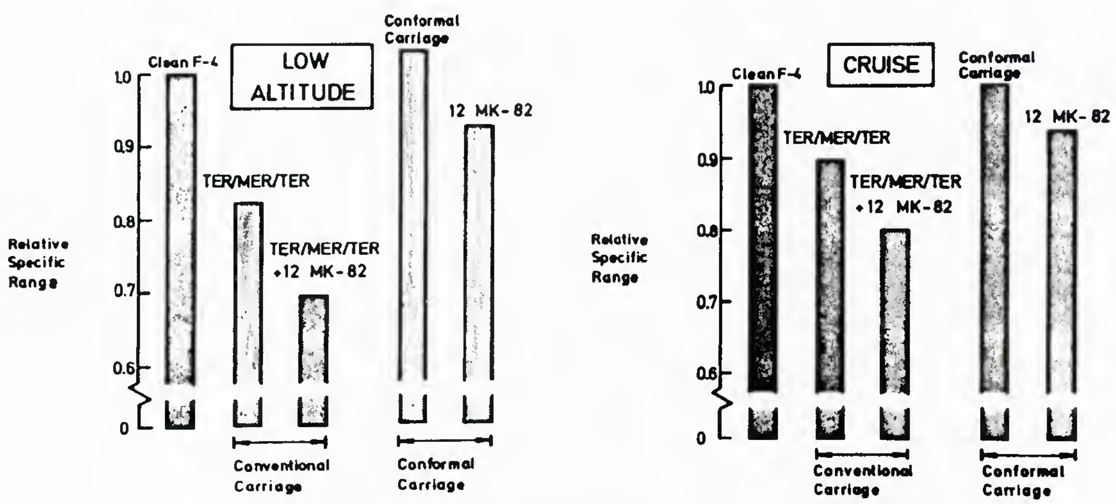


Fig. 22 SPECIFIC RANGE
Conventional / Conformal Carrige

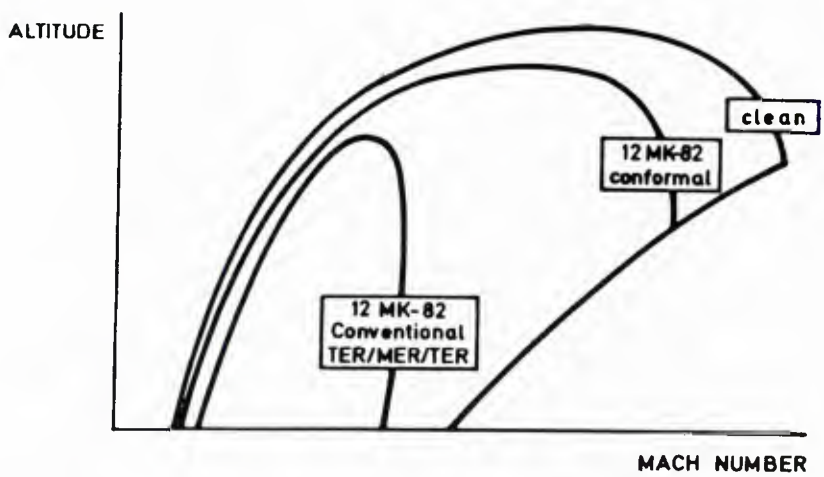
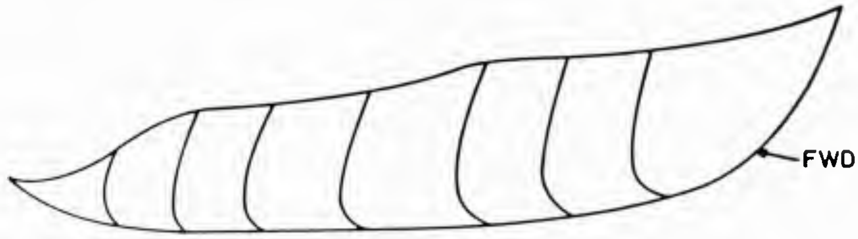


Fig. 23 FLIGHT ENVELOPE
clean a/c-conventional-conformal carriage



CONFORMAL FAST PACK FUEL PALLET

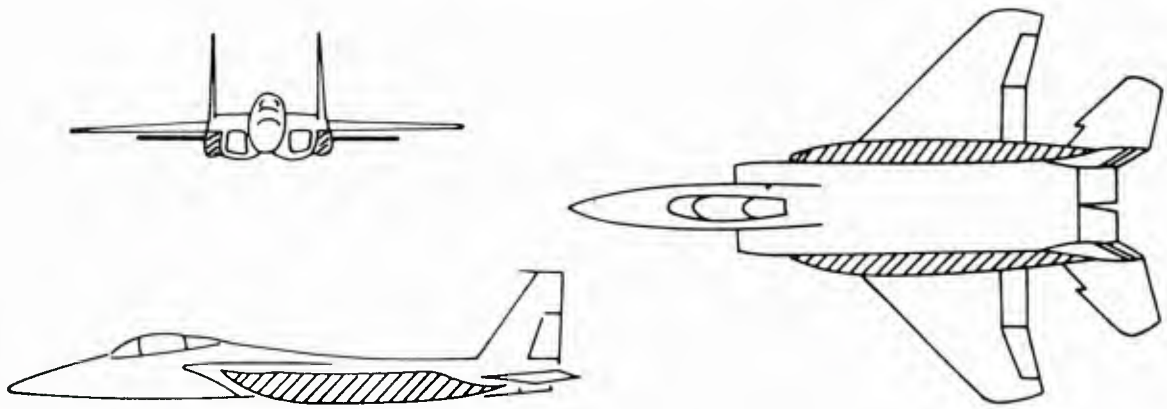


Fig.24 F–15 FAST PACK INSTALLATION

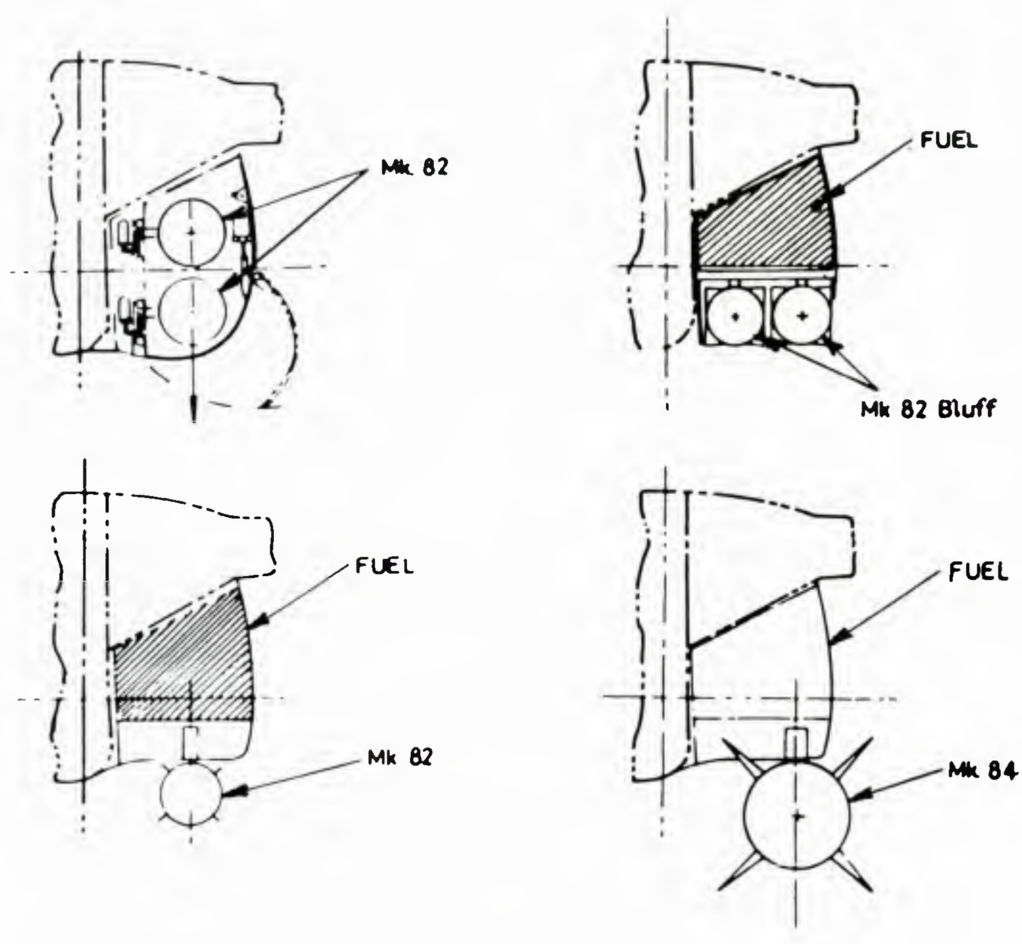


Fig.25 FAST PACK STORE LOADINGS

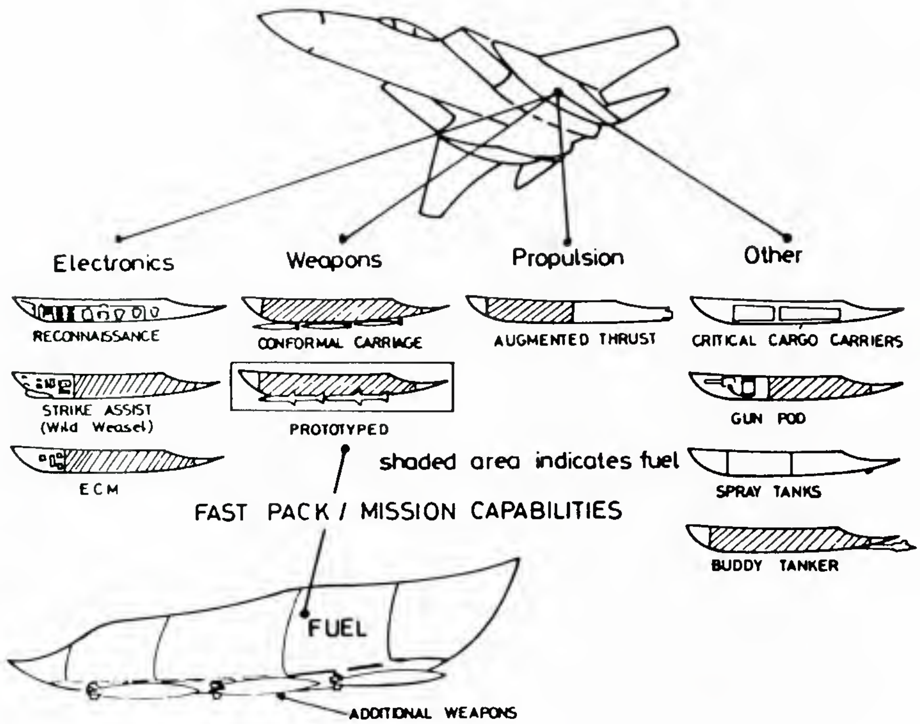


Fig.26 F–15 CONFORMAL WEAPONS /FUEL PALLET

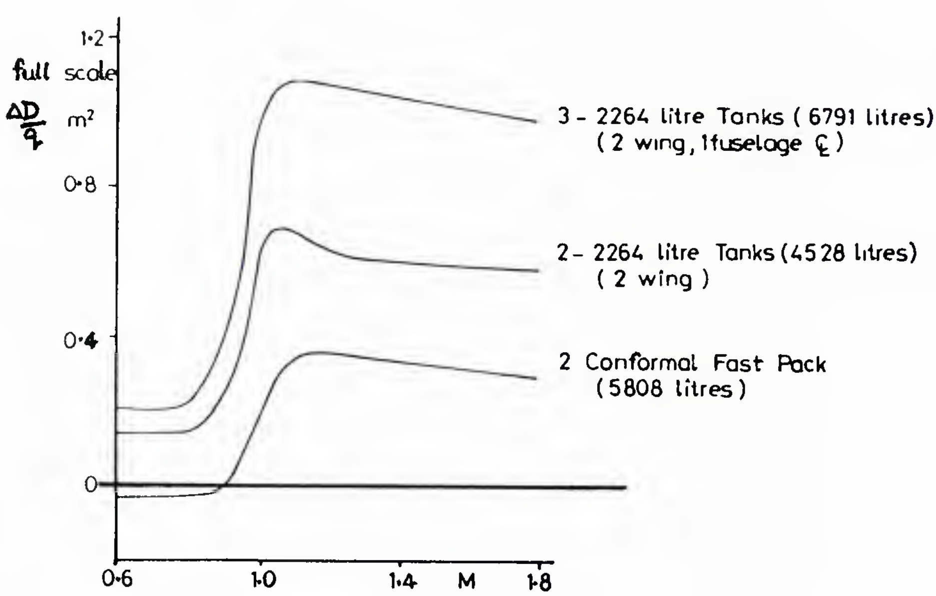


Fig.27

CONFORMAL VS. CONVENTIONAL FUEL TANK INSTALLATIONS, F–15

DESIGN OPTIMIZATION FOR A FAMILY OF MULTI-ROLE COMBAT AIRCRAFT

by

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SUMMARY

The future multi-role combat aircraft design process is used as an example throughout this lecture. At the early stage of the design, requirements of the French Air Force and Navy and other potential customers (European and other countries) are studied very closely. Then the main technological improvements - from the existing aircraft - that are needed to meet these requirements are clearly defined. The improvements are achieved by an optimization process carried throughout each and all aircraft design disciplines, involving an intensive use of the very large range of design and test tools available from the aircraft company and state research establishments. Because of the numerous technical innovations which will be introduced in the future combat aircraft, an in-flight demonstration aircraft has been judged necessary. The RAFALE demonstration aircraft, and the evolution into a future family of multi-role specific versions, will be presented.

I - INTRODUCTION

Since its foundation, the AMD-BA company has conceived 92 prototypes, the RAFALE demonstration aircraft being the latest in line (figure 1).

This experimental aircraft is part of the more general RAFALE programme, which concerns the development and industrialization of a family of new generation combat aircraft, designed to equip the French Military Forces in the middle of the next decade.

The following description is intended to illustrate the process which ensures design optimization of this family of multi-role combat aircraft.

2 - REQUIREMENTS

At the early stages of design, it is essential to study very closely the requirements of the staff of the French Air Force and of the French Navy and of other potential customers (European or other countries).

The French Air Force requires a multi-role aircraft able to carry out ground strike missions as well as air superiority missions and even air defence missions. It must cover an extensive flight envelope, have a maneuverability associated with a flying comfort significantly higher than that of present day aircraft, be capable of operating from short runways. Its carrying capacity and its weapons system shall ensure a large operational efficiency, which will also be obtained from its discretion (see figure 2).

The French Navy requires defence and air superiority aircraft to ensure the protection of its aircraft carriers and to carry out strike and reconnaissance missions. The maneuverability characteristics requested are very close to those of the French Air Force ; the same applies to approach speed, the thrust-to-weight ratio, the carrying capacity of external stores...

3 - THE OPTIMIZATION PROCESS

The design of the new family of combat aircraft results from an optimization process, which takes into account, at the utmost, the interaction between the various disciplines involved, such as aerodynamics, structure, propulsion, systems (see figure 3).

The more and more ambitious targets, involved by the previously mentioned requirements, as well as the essential target of the best cost/efficiency ratio, have moreover required extensive progress in the new technologies which have been included in the optimization process.

3.1 - THE AERODYNAMIC CONFIGURATION AND THE AIR INTAKES

Many preliminary studies have been carried out, completed by wind tunnel tests. Several configurations adapted to the low speed targets have been studied (see figure 4). For cost and simplicity reasons, the compromise has been orientated towards a delta-canard configuration. Performance in combat has been studied for various aircraft configurations (see figure 5) so as to determine the influence of the wing area, the aspect ratio, the thrust-to-weight ratio and thrust deflection devices or moving wing control surfaces. Once again, the delta-canard configuration has proved to be superior.

On the basis of this configuration, several other possible solutions could be studied concerning the position of the wings (high, medium, low), the position and number of fins (single fin, fuselage or wing double fin), the position of the air intakes and the type of protection.... (see figure 6).

Finally, the AMD-BA selected the following twin-engine configuration :

- double sweep-back delta-wing with high aspect ratio,
- large area active canard fins,
- semi-ventral "pitot" air intakes,
- single fin with large rudder.

The choice of this new configuration is the fruit of long experience and of the art of using it in the "façon DASSAULT".

In fact this configuration is in line with the family of delta wing aircraft which started with MIRAGE III aircraft and which, later, gave birth to MIRAGE 2000 aircraft then to the "canard + delta wing aircraft" (see figure 7). This latter configuration dates from the "MILAN" aircraft which, in 1969 with its retractable "nose fins", was the first attempt within DASSAULT to decrease the relatively high approach speed of MIRAGE III aircraft (180 kts). Then in 1979 it was the MIRAGE 4000 aircraft and in 1982 the MIRAGE III NG aircraft. The MIRAGE 4000 aircraft is equipped with fixed canard fins, designed to improve its maneuverability, which can be disengaged in case of multiple failure of the flight control system. This gives back stability to the aircraft and enables more traditional flying control.

It is certain that the RAFALE demonstration aircraft and the new family of aircraft which issues from it, will owe very much to the MIRAGE 4000 aircraft. This twin-engine aircraft has enabled experimentation of certain points inherent to the configuration retained for the RAFALE aircraft. For instance, even though they are very different in size, it is important to note that at the level of the shape and sweepback of the canards and of the position of the wing leading edge relative to the canard, RAFALE is a certified true copy of the MIRAGE 4000 aircraft.

For those who wonder why the "delta-wing" family has been momentarily interrupted with the MIRAGE F1 aircraft, I would like to recall briefly that to give a successor to the MIRAGE III aircraft, DASSAULT had chosen to abandon the delta configuration and to adopt the sweptback wing configuration to decrease the approach speed from approximately 180 kts to 140 kts with identical performance. The introduction of fly-by-wire controls, which enable artificial stabilization of an intrinsically unstable aircraft, allowed us to re-use the delta configuration for the MIRAGE 2000 aircraft which, while offering an appreciable maneuverability gain, remained within the 140 kts approach speed.

To come back to the delta moving canard configuration such as it is on the RAFALE demonstration aircraft, the advantages are multiple and we cannot go too far into details. This has already been done within the AGARD during a lecture at Trevise in April 86 by one of our aerodynamics engineers. We simply recall that this configuration enables :

- excellent wing efficiency, especially at high angles-of-attack, due to deflection of the air flow on the wing by the foreplane,
- extensive control of the aircraft's centre of gravity, thanks to the aerodynamic centre effect created by the canard. As you know, it is the mastery of longitudinal balance that guarantees high maneuverability throughout the flight envelope.

It has been proved in combat simulation that the negative static margin obtained, thanks to the fly-by-wire controls, which was optimum, depends on the optimum limit of maneuver, itself corresponding to the best CL max. The selection of negative static margin thus made, a canard dimension linked to the selection of the aircraft c.g. position is obtained (see figure 8).

- a certain number of new FCS functions, as for instance gust alleviation, decisive for multi-role aircraft. In fact the possibility of delaying the accelerations felt by the pilot at high speed and low altitude (penetration mission) makes possible the selection of larger wings which leads to an improvement of the aircraft qualities in the Air-to-Air dog fight (air superiority mission).

At last, linked to the delta canard configuration, the single fin solution has proved to be the best one.

The semi-ventral pitot air intakes, which are of an entirely new design issuing from many computations and tests, meet specific technological requirements :

- improvement in air intake efficiency at high angle-of-attack thanks to the protection provided by the forward fuselage,
- improvement in the quality of air supplied to the engines by increasing the stationary and unstationary homogeneity of the airflow,
- maintaining a Mach 2 capability, while at the same time achieving simplicity : no moving devices or bleeds,
- finally, complete separation of the right and left air intakes so that misfunctions of one does not affect the other engine, and also to allow sufficient space for installation of a forward retraction nose gear, leaving a large amount of space for carrying long underfuselage stores.

3.2 - SIZE

The selection of size is a decisive step in the fighter design process because then it creates an unavoidable restraint which will affect all other aspects.

From the requirements mentioned in the operational programme sheet which specify a certain number of data, studies of parameters lead to the selection of the optimal size. These studies cover the following main parameters :

- thrust,
- area,
- instantaneous turn rate (or approach speed),
- sustained turn rate,
- rate of climb,
- combat weight.

The effect of these parameters on the result is shown on figure 9.

On the RAFALE demonstration aircraft, this optimization has allowed the design of a twin-engine aircraft which is smaller than the other existing twin-engine aircraft of equivalent installed thrust (TORNADO , F 18) and even much smaller than the other highly motorized twin-engine aircraft (MIRAGE 4000, F15, F14).

At last, it must be recalled that the aircraft size problem has been discussed during the European cooperation feasibility studies with England, Germany, Italy and Spain. Since the size of the aircraft finally retained for the EFA project was too large, France had to withdraw.

Since then, the size of our design has been reconsidered and reduced, the basic version of the future aircraft is smaller than the demonstration aircraft with an empty weight of approximately 1 tonne less ; its dimensions are comparable to the MIRAGE 2000 single-engine aircraft (see figure 10).

3.3 - USE OF NEW MATERIALS

a) Composite materials

Since 1975 approximately, as shown on figure 11, AMD-BA have achieved in this field a progressive and continuous step forward during which it is worth noting that military and commercial fields were complementary to one another.

This has only been possible by the use of a wise and strict methodology , shown on figure 12, consisting in dividing the development of any new solution into three stages :

- experimentation on the ground
- application in flight
- integration on aircraft.

In AMD-BA this methodology is applied for the introduction of any new technology, whatever the field may be, before going to industrialization.

Three main examples will highlight the spectacular character of the technological breakthrough of AMD-BA in the field of composite materials :

- in 1978, the FALCON 50 was the first passenger transport aircraft with a vital component - the outer aileron - made of carbon fibre to be certified by the FAA,
- in 1979, the MIRAGE 4000 was the first aircraft to incorporate a large carbon fibre self-stiffened structure - the fin unit - also used as a fuel tank,
- in 1985, the FALCON V10F was the first transport aircraft to be certified with a one hundred percent carbon fibre wing.

The so-obtained progress have been used in the RAFALE programme and firstly on the demonstration aircraft. Composite materials are used not only for the control surfaces (elevons, rudder, canard), and the wings -for which a new high modulus fibre (IM6-5245C) is used for the very first time -, but also for the fuselage front section (cockpit structure (see figure 13), equipment bay), central section (complete fuel tank) and rear section (below engine area).
All landing gear doors as well as numerous access panels are made from composite material (see figure 14 and 15). The RAFALE demonstration aircraft also incorporates Aramid fibre for numerous elements such as wing-to-fuselage fillets, fairings and the nose radome.

Altogether, composite materials account for over a fourth of the structure weight.

b) Aluminium-Lithium

To cope with the competition of composite materials, metal workers had to find a solution : the aluminium-lithium alloys incorporate the required improvements. Indeed, with a proportion of 2.7 % of lithium for instance (beyond 3 % the metallurgical balances are broken) the density decrease is 10 % and the rigidity increase is 8 % relative to conventional aluminium alloys.

With a view to an increasing use of these new alloys in our aircraft, studies have been carried out in connection with the metal workers, they have more particularly dealt with :

- forging of ingots,
- thermal treatment,
- mechanical machining,
- chemical machining (development of baths),
- study of chromic anodic protection,
- geometric evolution and redressing of parts during and after machining,
- checking of weight saving and rigidity increase on samples and test parts.

Figure 16 shows the applications studied on the RAFALE demonstration aircraft. The zones retained deal with the fuselage skin panels and the inner panels of the engine tunnel. Furthermore, two fin attachment frames have been entirely machined.
The use of massive parts is under study and particularly depends on the feasibility of large blocks and the improvement of their mechanical properties.

Thus, the use of Aluminium-Lithium alloys could lead to a structural weight saving of 10 to 15 % for the future aircraft, while keeping the means of transformation and manufacture used at the present time for conventional alloys.

c) SPFDB

This revolutionary technology which results from the combination of superplastic forming and diffusion bonding, takes advantage of the property of some types of titanium alloys to stretch by up to 800 % and allows the manufacture, in a single hot forming operation, from thin flat plates, of self-stiffened structural elements of complex shape.

Since 1978, AMD-BA has developed this technique (see figure 17) : it has been incorporated for the first time in production on the strake of MIRAGE 2000 aircraft. It has shown simultaneously, a rare occurence :

- a weight reduction due to the decrease in thickness ensured by titanium,
- a cost price reduction, involved by the fact that the baking cycle also achieves assembly and enables the suppression of most fasteners.

The process has been used for the manufacture of the wing leading edge slats of the RAFALE demonstration aircraft.

We are studying the extension of this process to other components such as : canards, air intakes, canopy framing,...).

Remarks

For technological reasons (limiting thickness of titanium) the weight reduction can be subject to limitations, which leads to the idea of transferring the SPFDB to new aluminium alloys (SPF on aluminium already exists, but not the combination). An interesting example can be seen here in which manufacturing problems lead to new metallurgical research.

d) Conclusion

As a whole, 35 % of RAFALE's structural mass are made from various new materials, which, as far as we know, constitutes a world premier for a combat aircraft.

On the future aircraft, their use will be at least as large but may be different owing to the competition between aluminium-lithium alloys and composites.

3.4 - FLIGHT CONTROL SYSTEM

In this field also, the technological advance made in AMD-BA, marked very soon by the decisive stage which was the creation of the Dassault Equipment Division (see figure 18), has each time given the answer to - and has even often gone beyond-the operational requirements.

Here again, the permanent compromise between the essential innovation and the respect of the traditions tending to use a maximum of proven solutions, has been the main element of the development of the flight control systems used on our aircraft.

Figure 19 shows this evolution in time and how we gradually replaced the simple direct mechanical links by fly-by-wire control systems.

On the RAFALE demonstration aircraft a further step has been made with the generalization of digital systems.

The resulting CCV design, linked to the aerodynamic configuration retained, ensures an optimal utilization of the numerous servo-controls (17 control surfaces and 2 engine servo-controls (see figure 20)) and thus enables the introduction of a certain number of functions (see figure 21).

Some of them have already been tested in flight on the MIRAGE 2000 aircraft. The others, which are new, will be developed on the RAFALE demonstration aircraft to be,if possible, integrated in the future versions.

The use of optical fibre for data transmission will be evaluated.

3.5 - AIRFRAME LAYOUT

It has become traditional within the AMD-BA to manufacture at the beginning of the design process an entire full-scale layout mock-up (see figure 22).

This mock-up becomes essential to fit out an aircraft of reduced size, using for the airframe a large part of new materials where retrofit is difficult and receiving a large number of equipment (operational or ancillary equipment), which are not on the shelf and the overall size of which has not been entirely defined.

Due to this mock-up, we can study and solve more easily and sufficiently soon the problems of location of equipment and the problems of running the numerous related wiring and piping.

But it also enables every one, and in particular the future operational users, to help us all along the design, so as to consider the correct accessibility to the circuits and equipment.

Thus this method enables us to optimize the ease of operation and maintenance of the aircraft. This aspect is of prime importance for the design of a family of multi-role aircraft (possible utilization on runways or on aircraft carriers).

3.6 - INSTALLATION OF THE PILOT AND MAN/MACHINE INTERFACE

Two main criteria, proper to future combat aircraft, had to taken into account, in the design of the cockpit :

- the improvement of maneuverability in the entire flight envelope, which results in an appreciable increase of accelerations (see figure 23) and of their duration,
- the extension of the operational functions of a multi-purpose weapons system.

Very soon, it seemed to us that an optimum answer to these two criteria would necessarily lead to a complete revision of the installation of the pilot in the aircraft and, concurrently, to reconsider entirely the man/machine interface.

The difficulty of the problem has led us to examine all the solutions, including the most advanced ones (inclined ejection seat). This was covered by the OPE study (Organisation du Poste d'Equipage) initiated by the French Official Services.

The OPE study : following on a computer augmented anthropometric study, simple mock-ups have quickly shown that it was possible to work correctly in a highly reclined ejection seat, provided that the upper part of the torso is straightened up by a support at the level of the shoulder blades. With tests made in centrifugal machines we have checked that an angle up to 50° ensures an excellent protection against load factors - the reclined position lowers the blood column between the brain and the heart.

Beyond that, the pilot started to have difficulties in breathing (chest extension). Moreover, as from a certain inclination, the surfaces capable of receiving flying or operational instrumentation were becoming non existent or inacessible.

Application to the RAFALE demonstration aircraft

When defining the demonstration aircraft, it has been decided to experiment in flight the solution studied within the OPE. Several problems, inherent to the reclined installation of the ejection seat, remained to be solved :

- to eject from the aircraft without delay and in good conditions in case of emergency. That is to say to keep a sufficient ejection path,
- to cope with the quasi disappearance of the instrument panel.

Furthermore, we had to check if the performance of existing ejection seats enabled this type of installation since the main problem was the clearance above the fin during ejection. From this point, trajectory computations followed by tests have quickly proved feasibility.

Thorough studies and detailed mocking-up sessions have allowed us to obtain a satisfactory, original and ergonomic compromise solution, shown by figures 24 and 25. This new installation of the pilot and the new related man/machine interface can be briefly described as follows :

- ejection seat inclined at a 32° back angle (possibility 37°)
- flying control according to the HOTAS concept "hands on throttle and stick", with the control stick on the right and a throttle lever on the left (only one control for two engines), both having a low displacement and integrated controls. Their high position, associated with the presence of elbow rests, avoids blood accumulation in the arms under large load factors.
- flight and mission parameters synthesized on displays generated by the latest technologies such as :
  . head-up display with holographic imaging,
  . head-level display collimated to infinity,
  . lateral multichromic head-down display,
  associated with a multi-function keyboard and voice control.

The experiments in progress show, thanks to these improvements, that it is still possible to improve the comfort (reduced workload and physiological restraints) and therefore the operational efficiency of the pilot, and to reject a certain trend of thought according to which man now constitutes a limiting factor in the development of modern combat aircraft.

It must be added to this, due particularly to a bubble canopy and very low position of the canopy arches, that the pilot has an exceptional external visibility, which is in no way obstructed by the canards.

3.7 - GENERALIZED INTEGRATION OF THE AIRCRAFT SYSTEMS

With the RAFALE demonstration aircraft, a large step towards the general integration of the systems has been made.

In addition to the flight controls which have been already mentioned, the aircraft systems and circuits, such as fuel, hydraulics, electricity, air conditioning, engine control, navigation and communications, make wide use of digital technology, with information transit and exchange being made over two centralized digital data bus lines. Thus the pilot does not have to worry about monitoring the systems ; he will only be warned in the event of failure, if this is strictly necessary, and will be provided with the information required to take rapid and efficient action.

Experimentation in flight of this integration concept will enable the optimization of the really necessary integration level in the future operational aircraft.

3.8 - STORES

Designing a multirole combat aircraft means providing a high weapon-carrying capability ; in this respect, the RAFALE is particularly well placed since it has, in addition to its internal gun, twelve hardpoints allowing approximately 7 tonnes of external stores to be carried.

We have already mentioned previously that the architecture of the aircraft air intakes, nose and main undercarriages gives the capability for a large store to be carried under the fuselage, which is essential to achieve certain Air-to-Ground missions (see figure 28).

Certain configurations, such as those with air-to-air missiles conformal to the fuselage, have been designed especially to reduce drag and radar signature. Figure 29 shows the configurations which have been tested in the wind tunnel for under fuselage tandem-mounted missiles. The structural optimization has enabled the installation of the missile ejectors inside the aircraft.

This store carrying capacity, which is exceptional for an aircraft of this size, has been obtained by opting for a mid-fuselage wing location and designing a special linkage system for the nose gear that minimizes the space required under the front section for retraction and extension of the gear.

Here we have (figure 30) an air-to-air configuration showing 8 MICA missiles and 2 MAGIC missiles.

At last, its multitarget capability stems also from its aptitude to carry out long range missions : to achieve this, it has a high internal fuel capacity. In fact the internal fuel-to-empty weight ratio is the highest for fighter aircraft in this category, which reflects the efforts made to optimize the use of the aircraft's internal space.

Figure 31 gives the envelope of the Air-to-Ground configurations, with in particular the 2000 l drop tanks at wing station 1.

4 - MEANS FOR COMPUTER AIDED DESIGN

The generalized optimization process which we have just described, could only be attained thanks to the considerable and continuous increase of the design and development means. We now propose to consider shortly the main means available.

4.1 - IN CAD-CAM : CATIA (Conception Assistée Tridimensionnelle InterActive)

We started more than fifteen years ago a policy of development and operational utilization of CAD-CAM.

In this view, the decision of developing the firm's software "CATIA" has been a decisive step.

Within our design offices, the basic tool remains the traditional drawing board, the latter is henceforth completed by CATIA work stations (figure 32). Progressively, we encounter the same type of work station in an increasing number of specialized departments taking part in the design of the project : aerodynamics, structure, systems...

The role of CATIA does not stop at the design phase but as any modern CAD-CAM tool, and probably more than others, it is present all along the continuous line which goes from design to manufacture, maintenance and documentation.

Thus the generalized and multidisciplinary utilization of CATIA (figure 33) enables an increase of efficiency and coherence of the complete process of development, and thus improves the quality of the product, which in particular profits from better accuracy.

The RAFALE demonstration aircraft is, also in this respect, an eloquent example.

As is the penetration of the CATIA system all over the world : nowadays more than 500 companies use the CATIA tool in more than 7000 work stations.

4.2 - IN AERODYNAMICS

Computational aerodynamics, which is in fact at the origin of the CATIA development (since the shape drawing is initially a by-product of the system designed by the aerodynamics engineers for computation) is a rapidly evolving discipline benefiting largely from advances in computer technology and on the other hand it constitutes a primary driving force for computer technology development by its outstanding computation performance requirements.

The codes used, which are of varied complexity and adapted to the various stages of the project, have been and will be obviously widely used within the RAFALE programme. As their contents are the subject of regular correspondance in AGARD, we limit ourselves here to an illustration of their application on the RAFALE demonstration aircraft (figure 34).

Often opposed in the past to computational aerodynamics, wind tunnel tests still constitute an essential element of the aerodynamic design of the aircraft, but in this respect we note a significant change.

Computational aerodynamics now enable configuration screening and optimization at the very preliminary design stage. Thus, from the retained configurations we immediately come to a relatively reduced number of models, whose design and manufacture delays are greatly reduced thanks to the utilization of CATIA (within a ratio from 4 to 1) and whose wind tunnel tests, enable us to cover quickly the whole flight envelope.

From this, the accurate check and the validation of various solutions as well as the final selection become possible within acceptable delays.

This proves that more than ever experimental and computational aerodynamics must not be competitive but complementary disciplines at every stage of design.

Anyway wind-tunnel testing remains important for identification of vehicle characteristics after configuration freeze and to generate data required by flying quality simulations, performace evaluation, structural analysis, etc...

There are three particularly important areas in combat aircraft development where wind-tunnel testing plays a unique role :

- high angle-of-attack behaviour characterization,
- air intake performance and flow distortion,
- tests related to external store installations, release, ejection and firing.

RAFALE models installed in various wind-tunnels, to carry out the tests required by the above topics, are shown on the figure 35.

4.3 - IN STRUCTURE

In this field the finite elements computer code, called "ELFINI", has become an essential tool.

The development of this code, operational in the AMD-BA stress division for nearly twenty years and continually enriched since, has also been made possible thanks to the increase of computer performance, the advent of intelligent terminals and high resolution colour screens and to progress made in numerical analysis and programming.

It is now possible to solve very large scale structural problems (close to 200 000 degrees of freedom) and to carry out the iteration cycles required by structural optimization or by non-linear computation within an acceptable time and cost schedule.

Without lingering on the numerous possibilities of the ELFINI code, which has also been the subject of AGARD correspondance, we show its application on the RAFALE demonstration aircraft on figure 36.

Additional advances are predicted in the near future in the following areas :

. integration of the ELFINI code in the CATIA CAD/CAM system,

. improvements in damage tolerance analysis,

. prediction of buckling and postbuckling,

. transonic unsteady aeroelasticity,

. active control,

. multidisciplinary optimization,

. structural behaviour in high temperature environment.

Most of them will be used for the first time operationally in the continuation of the RAFALE programme. It is notably the case for the prediction of buckling and post-buckling, which will enable the optimization of the rear fuselage skin panels.

4.4 - SIMULATION

In the area of simulation, which has become an important development and evaluation tool, recent activities were orientated in three directions :

a) Update and enhancement of the AMD-BA engineering simulator capabilities for advanced flight control design and flying qualities studies.
At the beginning we can study in a dome the behaviour of the "entirely simulated" aircraft, then once the servo-controls and the computers have been manufactured by Dassault Equipment Division, the connection with the simulator is made thus enabling perfect simulation of the aircraft.

b) Development of a multi-aircraft combat computer programme to synthesize and validate combat tactics.

c) Development of a flexible display tool for the design of cockpit symbology. It is the OASIS system (Outil d'Aide aux Spécifications Informatiques des Systèmes).

These tools - particularly the engineering simulator and the OASIS system - have enabled the ultra rapid design and development of the numerical fly-by-wire controls and the entirely new man/machine interface of the RAFALE demonstration aircraft. In addition, they have enabled the pilots to get used to and to grow familiar with these new systems as soon as possible, which is a true break with the past.

Finally one must add to these simulators, those which exist in Government Test Centres and which are widely used for the development of the cockpit, the integration of the weapons system and combat training : these are mainly the CEV (Centre d'Essais en Vol) and the CELAR (Centre Electronique de l'Armement) simulators.

Figure 39 shows the main means of simulation used. They will be obviously used all along the development of the new aircraft.

4.5 - CONCLUSION ON THE GROUND MEANS

To conclude this chapter, without going any further, we shall merely say that equivalent means are set into operation in all the other disciplines implicated in the development of the future aircraft, i.e. :

- New materials,
- Mechanical and acoustic vibrations,
- Propulsion,
- Circuits and equipment,
- Weapons systems including countermeasures,
- Electrostatic environment,
- Equivalent radar surface and infra-red signature.

The means concerning this last item are to be developped particularly due to the increasing importance assumed by discretion and stealth aspects, in the design of new generation combat aircraft.

In all these disciplines, the internal AMD-BA means and the means available either in the Government Test Centres or in private companies, are harmoniously complementary to one another.

Thus, they form a solid basis to establish the Dassault validation methodology, which judiciously puts together computation and ground experiments before going to the ultimate step : flight tests.

5 - FLIGHT TESTS

In this area, the RAFALE programme will be able to profit from 50 years of experience, which, thanks again to a well considered step-by-step policy, nowadays gives rise to an homogeneous entity which is certainly unique in the world.

This entity, based on an original organization, uses particularly efficient means.

The organization is characterized by an integration of flight tests in the previsions - partial tests - ground tests contrary to other companies or countries which differentiate clearly the flight tests from others even if they have to be integrated in specialized test centres. Figure 40 illustrates our integration of the flight tests.

The means used are essentially made of :

- a recording/analyzing system of parameters collected on board based on telemetry, which, as far as we know, has no equivalent in technology and performance. The architecture of this system is shown on figure 41.
- an airborne numerical data acquisition system using leading technologies such as hybrid circuits with LSI components as required. This system called "DANIEL 90" and supplied by Electronique Serge Dassault has a capacity of analysis of 32 000 pts/sec.

  As far as we know, this system is one of the most efficient flying in Europe at the present time, well adapted to the acquisition of data on all types of digibus (GINA, MIL-SDT-1553, COLLINS, PROLOG).

All this has already been used on the RAFALE demonstration aircraft, which has encountered an unprecedented rate of flight in our company.

The related test facility enables, all along the flight, a follow-up in real time of nearly 1200 parameters and enables the modification, if needs be, of the flight instructions and/or warning the pilot of a degradation of a parameter or an unexpected variation in flight conditions.

6 - EXPERIMENTAL SYSTEMS

In order to prepare the future combat aircraft, a set of experimental systems have been launched in the main fields concerned by the RAFALE programme. Figure 42 shows this set.

As concerns the aircraft, it is the RAFALE demonstration aircraft, which we have widely discussed all along this report. Its role was, let us recall it once again, to integrate in flight a maximum of new technologies (see figure 43) and thus enable through its experimentation the orientation of the technical decisions for the future aircraft.

It is also used as a reference to judge the ability to carry out various missions, notably those of the Navy, as well as to establish the provisional development cost file.

A brief schedule of the flight tests made is shown on figure 44. We can state positively that this aircraft has here and now proved the validity of the concepts considered for the future aircraft and confirmed the computed performance.

As concerns the engine, SNECMA has manufactured an M88 experimental engine which has been running on the test bench for more than one year and which has up to this day proved the thrust performance. The HP portion of this engine has been retained to be used as a basis for the definition of the production engine, the total thrust will result from the choice of the LP portion with which it is fitted.

It is anticipated that the RAFALE experimental aircraft will be used as a flying test rig for the M 88 engine in order to ensure as soon as possible its integration in the future aircraft.

As concerns the radar, an exploratory development has been launched to study the multitarget function, as well as an experimental radar RACAAS at TH-CSF, whilst ESD leads the work in the ANTILOPE family (a functional mock-up is launched).

As concerns the MICA missile, various designs were launched several years ago, concerning propulsion, seeker, launching system as well as its association with the multitarget fire controls.

By adding to these experimental systems other work relative to other components of the system and important steps in the discretion area, a large assembly of data has been established to enable the selection of the final configuration for the operational aircraft.

7 - THE FAMILY OF MULTIROLE COMBAT AIRCRAFT

All the work entered into within the RAFALE programme, and already concretized by the previously stated experimental systems, shall open out on a new family of multimission and multirole combat aircraft.

The optimized process described all along this report ensures the design of a basic version for the French Air Force, adapted to its various operational missions - ground strike - air superiority or air defence.

From this basic version, it will be possible to derive a version designed for the Navy thanks to the fact that we have taken into account, from the beginning of the process, the requirements proper to this version, namely :

- low approach speed and increased visibility,
- installation of an undercarriage capable of receiving a specific Navy landing gear with catapulting by the nose gear,
- space available for the attachment of an arrester hook at the rear,
- large ground clearance.

For certain European countries, RAFALE is an alternative aircraft, lighter and cheaper than the Eurofighter.

For export, RAFALE should be in the range of 7 to 10 tonnes aircraft, beyond MIRAGE 2000 aircraft.

8 - CONCLUSIONS

In a report established in 1973 by the Rand Corporation on AVIONS MARCEL DASSAULT, we read :

"Dassault's fundamental development policy is to minimize the extent of technical risk that is incurred at any single point in time. A given aircraft design, although it may appear to be novel, usually incorporates no more than one or two unique major design features...

Adoption of some of the forms of the Dassault process could well change American aircraft, and the industry that makes them, for the better..."

The 92 nd prototype of a long line, the RAFALE experimental aircraft is the achievement of this continuous and regular process of technical innovations which opens the way for a new generation of multirole combat aircraft (see figure 45).

FIG. 1 - RAFALE DEMONSTRATOR IN FLIGHT

- NEW GENERATION AIRCRAFT TO OPPOSE TO THE VARSOW PACT FORCES
- REPLACEMENT OF MIRAGE III E AND JAGUAR AT LOW COST TO HAVE AVAILABLE AIRCRAFT IN SUFFICIENT NUMBER
- THREE MISSIONS OF EQUAL IMPORTANCES
  - AIR SUPERIORITY ABOVE NATIONAL TERRITORY AND BATTLE DISPOSITION
  - LONG RANGE AIR-TO-GROUND AND INTERDICTOR STRIKE
  - LONG LOITER WITH FLIGHT REFUELLING
- GREAT AGILITY AND MANEUVERABILITY
- USE OF SHORT OR DAMAGED RUNWAYS
- LOW OBSERVABLE CHARACTERISTICS

FIG. 2 - FRENCH AIR STAFF REQUIREMENTS

Program Specifications
- Performance
- Mission Requirements
- Weapon System
- Economics

Design Stage	Design Task	Disciplines Involved
Conceptual	Research Data base collection Technology level selection Configuration gathering Parametric studies	• Aerodynamics • Propulsion • Weight Balance Inertia • Structures • Systems • Internal and External Layouts, Drafting • Costs/Economics • Ground Testing • Simulation • Environmental Impact
Preliminary	Design criteria selection Optimization Sizing Evaluation Configuration selection	
Detailed	Design refinement Integration Identification Design verification and documentation (drawings and technical data)	

FIG. 3 - THE AIRCRAFT PROCESS DESIGN

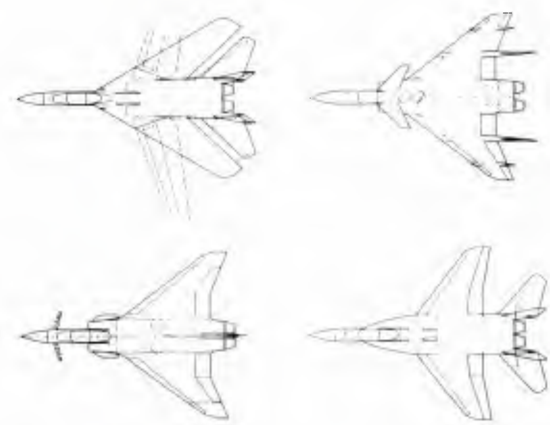


FIG. 4 - EXAMPLE OF LOW SPEED CONFIGURATIONS STUDIED

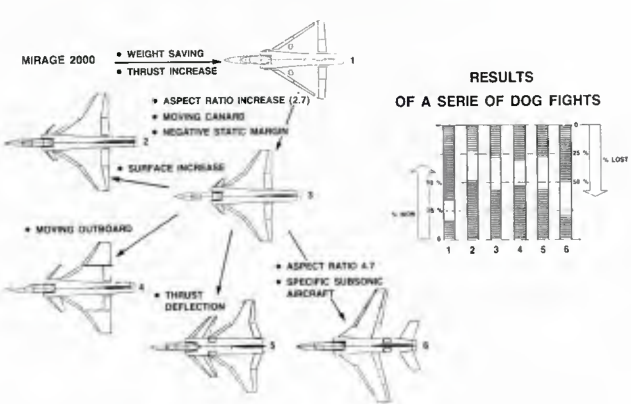


FIG. 5 - COMBAT PERFORMANCE OF NEW AIRCRAFT FORMULA

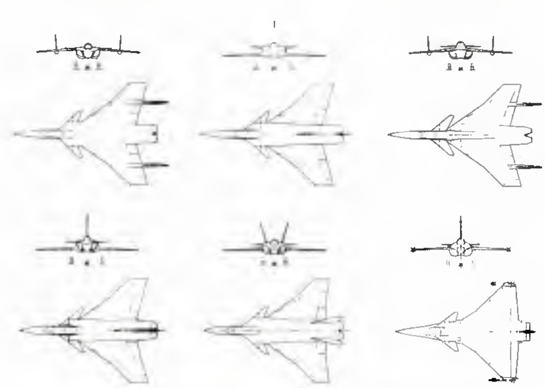


FIG. 6 - EXAMPLE OF DELTA-CANARD CONFIGURATIONS STUDIED

FIG. 7 - FILIATION OF DELTA WING AIRCRAFT AND CREATION OF DELTA-CANARD AIRCRAFT

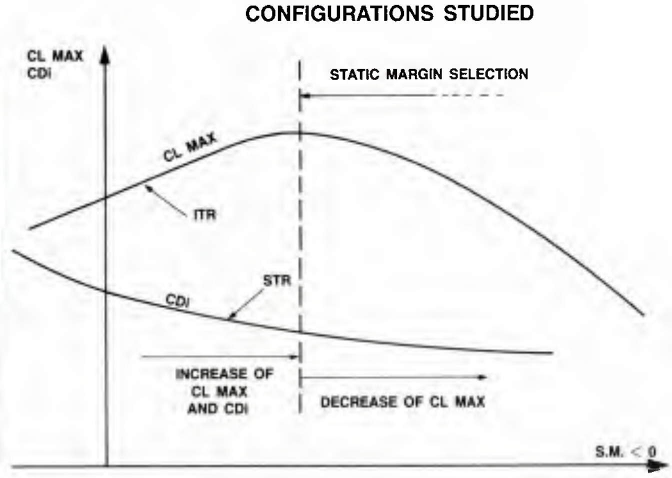


FIG. 8 - NEGATIVE STATIC MARGIN SELECTION

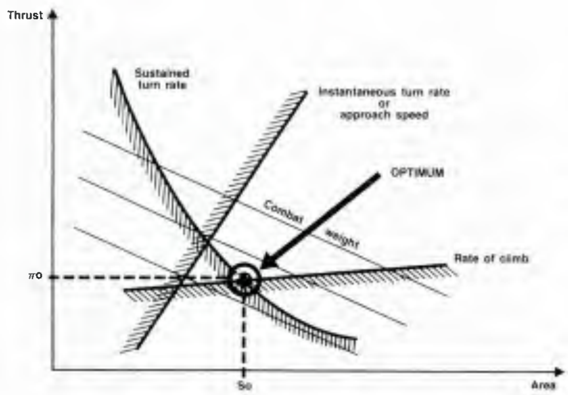


FIG. 9 - PARAMETER STUDY : AN EXAMPLE OF OPTIMIZATION

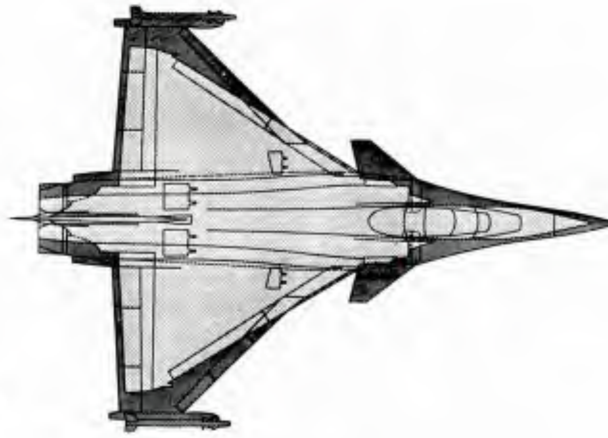


FIG. 10 - SIZE COMPARISON BETWEEN RAFALE AND MIRAGE 2000

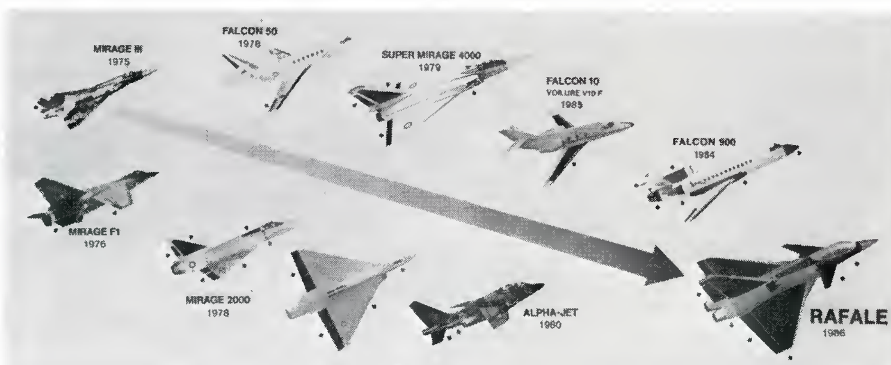


FIG. 11 - COMPOSITE MATERIAL IN DASSAULT-BREGUET AIRCRAFT FROM MIRAGE III TO RAFALE

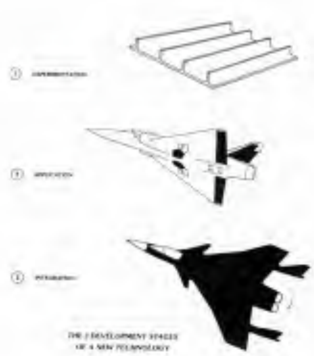


FIG. 12 - THE DEVELOPMENT STAGES OF A NEW TECHNOLOGY

FIG. 13 - RAFALE FRONT FUSELAGE CARBON FIBER ELEMENT

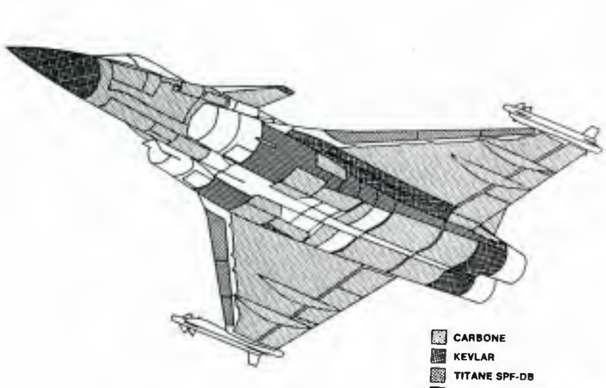


FIG. 14 - NEW MATERIALS IN RAFALE (BOTTOM VIEW)

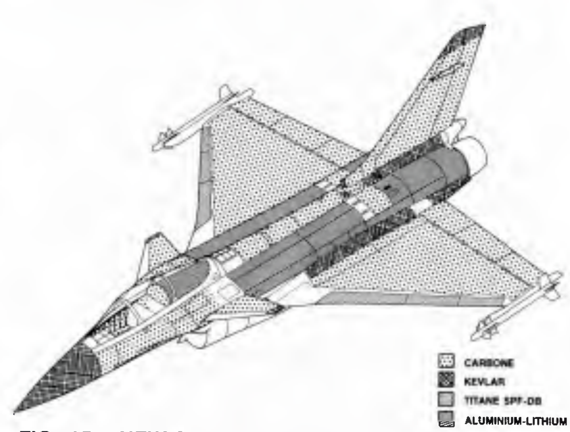


FIG. 15 - NEW MATERIALS IN RAFALE (TOP VIEW)

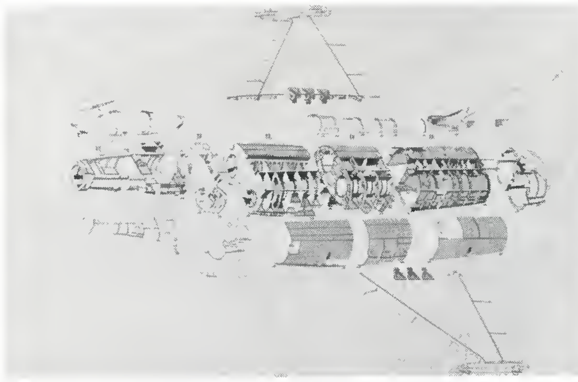
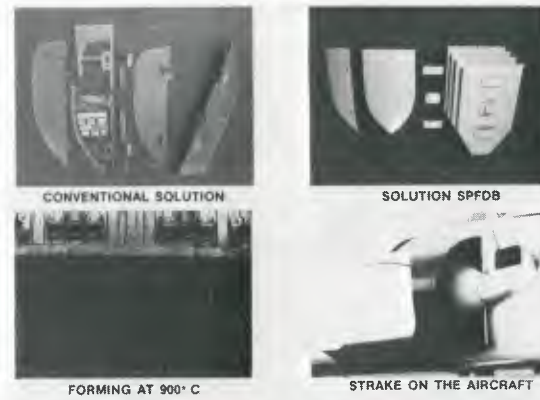
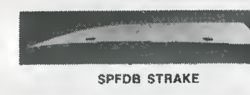


FIG. 16 - INTRODUCTION OF ALUMINIUM-LITHIUM STUDIED ON THE RAFALE

SUPERPLASTIC FORMING - DIFFUSION BONDING
MIRAGE 2000 STRAKE



CONVENTIONAL LIGHT ALLOY		SPFDB TITANIUM ALLOY
3.2 kg	WEIGHT	2.8 kg
10	PIECES	4
155	ATTACHMENTS	8



RAFALE LEADING EDGE SLAT
TA6V SPFDB

FIG. 17 - SUPERPLASTIC FORMING - DIFFUSION BONDING APPLICATIONS

In the fifties the penetration of aircraft in the sonic field required a new generation of flight controls resorting to servocontrols.

DASSAULT-BREGUET decided to built its flight systems on its own and to use the mechanical experience acquired in the field of propellers and engines. The Dassault Equipment Division (DED) was born.

The close and internal cooperation between the airframe designer and the manufacturer of flight control systems has been continued ever since. Associating the advances in aircraft performance with the advances in flight systems, this cooperation has led today to making aircraft fly at instable configurations thanks to electric flight controls.

The DED masters such technical fields as mechanical skill, high pressure hydraulics, servomechanisms and modern analogical and digital electronics. With a solid experience in design as well as in production, DED carries out specific high performance flight controls devoted for the aircraft and the weapons for DASSAULT-BREGUET and for other aerospatial Companies worldwide.

FIG. 18 - DASSAULT EQUIPMENT DIVISION

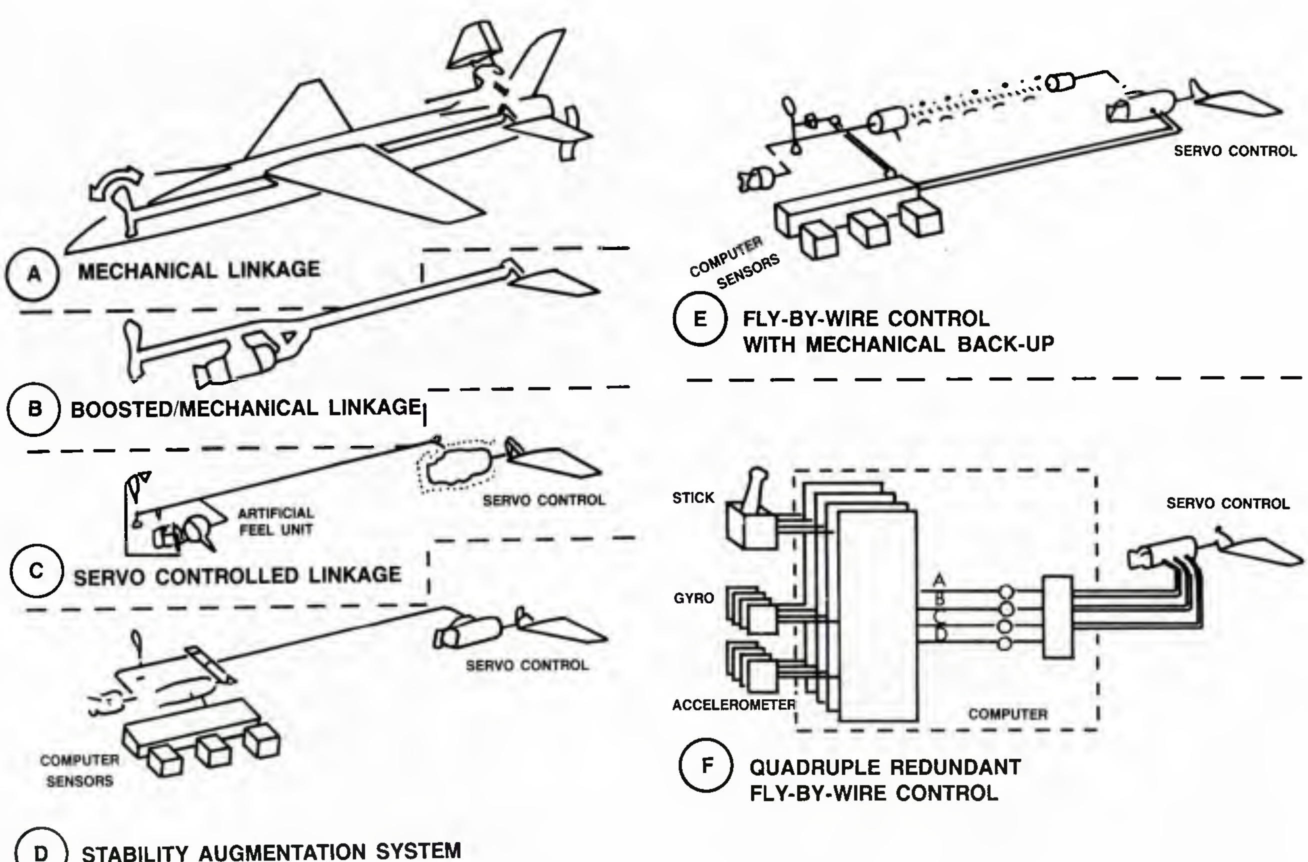


FIG. 19 - FLIGHT CONTROL SYSTEM DEVELOPMENT

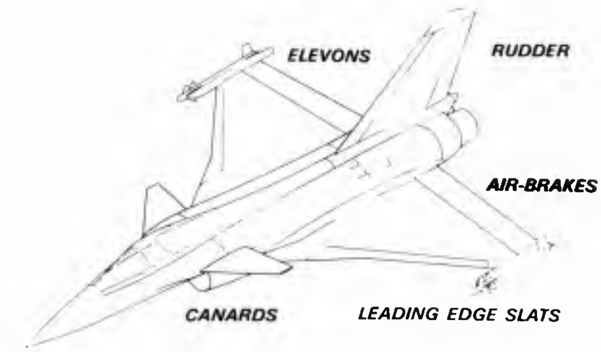


FIG. 20 - RAFALE - CONTROL SURFACES

— CLASSICAL FUNCTIONS (MIRAGE 2000)
- — STABILITY CONTROL ON THE THREE AXES
- — AUTOMATIC FLIGHT LIMITATION
- — CONFIGURATION CONTROL

— NEW FUNCTIONS
- — GUST ALLEVIATION
- — APPROACH MODE
- — HIGH ANGLE OF ATTACK CONTROL
- — STRUCTURAL LOAD MINIMIZATION
- — DIRECT LIFT CONTROL
- — ACTIVE FLUTTER SUPPRESSION
- — SECONDARY FUNCTIONS (ANTI-G SUIT...)

— CONNECTION FUNCTIONS WITH AUTOPILOT

FIG. 21 - RAFALE - FLIGHT CONTROL SYSTEM FUNCTIONS

FIG. 22 - RAFALE - FULL SCALE LAYOUT MOCK-UP

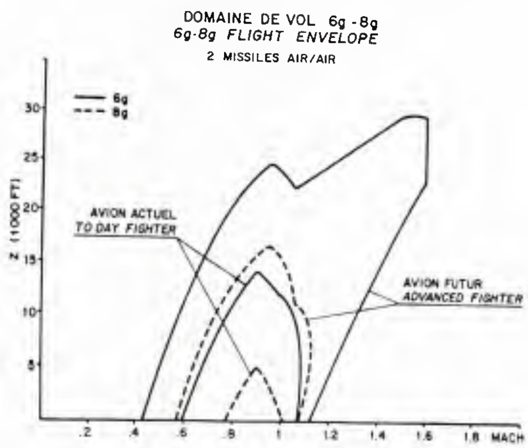


FIG. 23 - FLIGHT ENVELOPE COMPARISON BETWEEN TODAY'S AND ADVANCED FIGHTERS

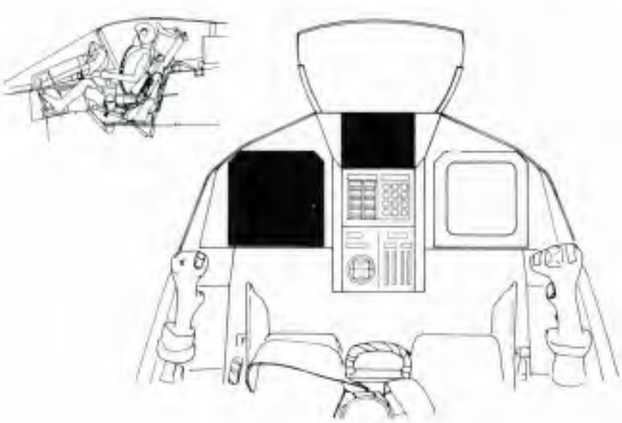


FIG. 24 - RAFALE - PILOT INSTALLATION AND COCKPIT

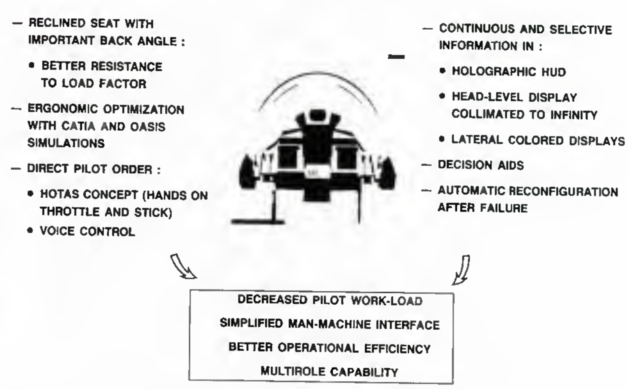


FIG. 25 - PILOT'S ENVIRONMENT

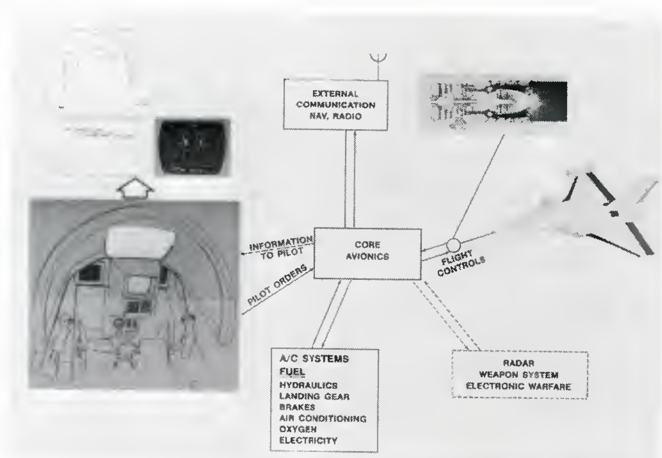


FIG. 26 - OVERALL SYSTEMS INTEGRATION

Fuselage : 1 station capable of two missiles in tandem arrangement

4 side stations

Wings : 1 station capable of one 2000 l extra fuel tank

1 station capable of one 1000 kg load

1 wing-tip station (self-defence missile)

Total : **12 carrying stations**

or **3 more carrying stations than on the Mirage 2000.**

FIG. 27 - RAFALE - CARRYING CAPABILITY

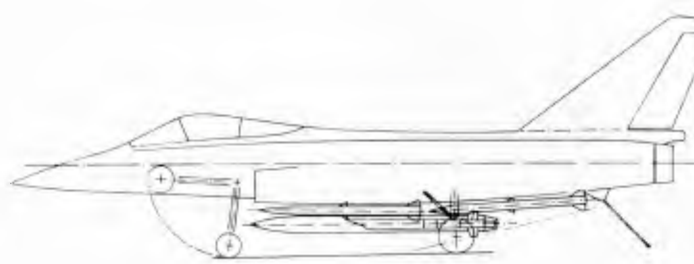


FIG. 28 - RAFALE - IMPORTANT CARRYING CAPACITY UNDER FUSELAGE

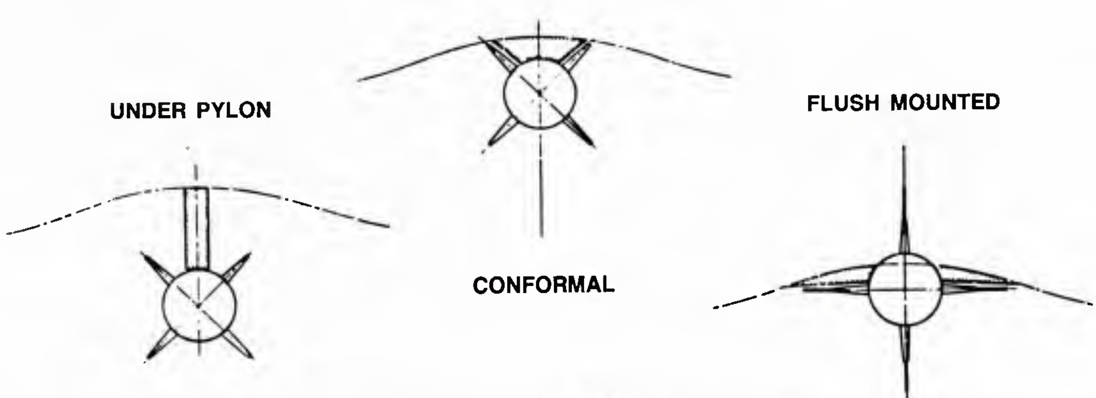


FIG. 29 - RESEARCH OF MINIMUM DRAG FOR UNDERFUSELAGE TANDEM MOUNTED MISSILES

FIG. 30 - RAFALE - 8 MICA + 2 MAGIC CONFIGURATION

FIG. 31 - RAFALE - CARRYING CAPABILITY

FIG. 32 - CATIA WORK STATION

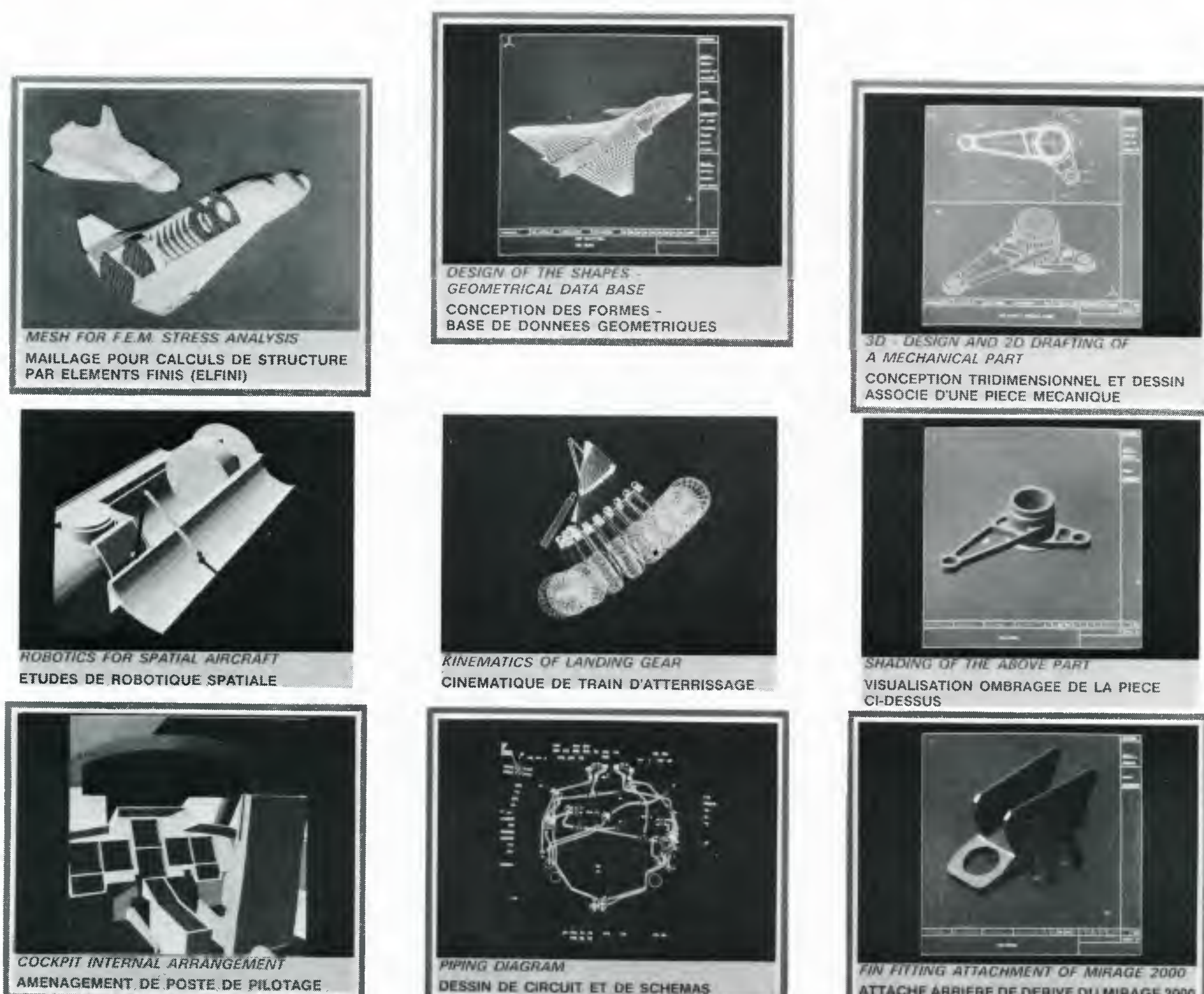


FIG. 33 - CATIA : CAD/CAM SOFTWARE IN AMD-BA

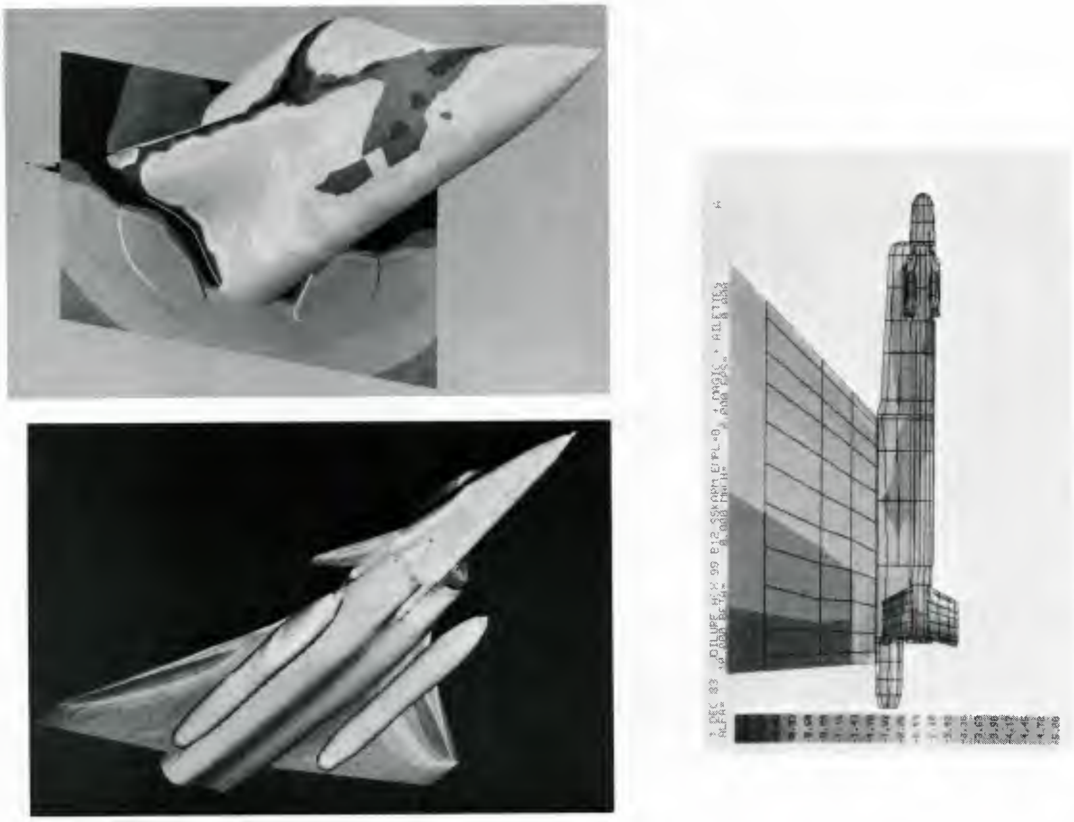


FIG. 34 - USE OF COMPUTATIONAL AERODYNAMICS CODES ON RAFALE

FIG. 35 - WIND TUNNEL TESTING OF RAFALE MODELS

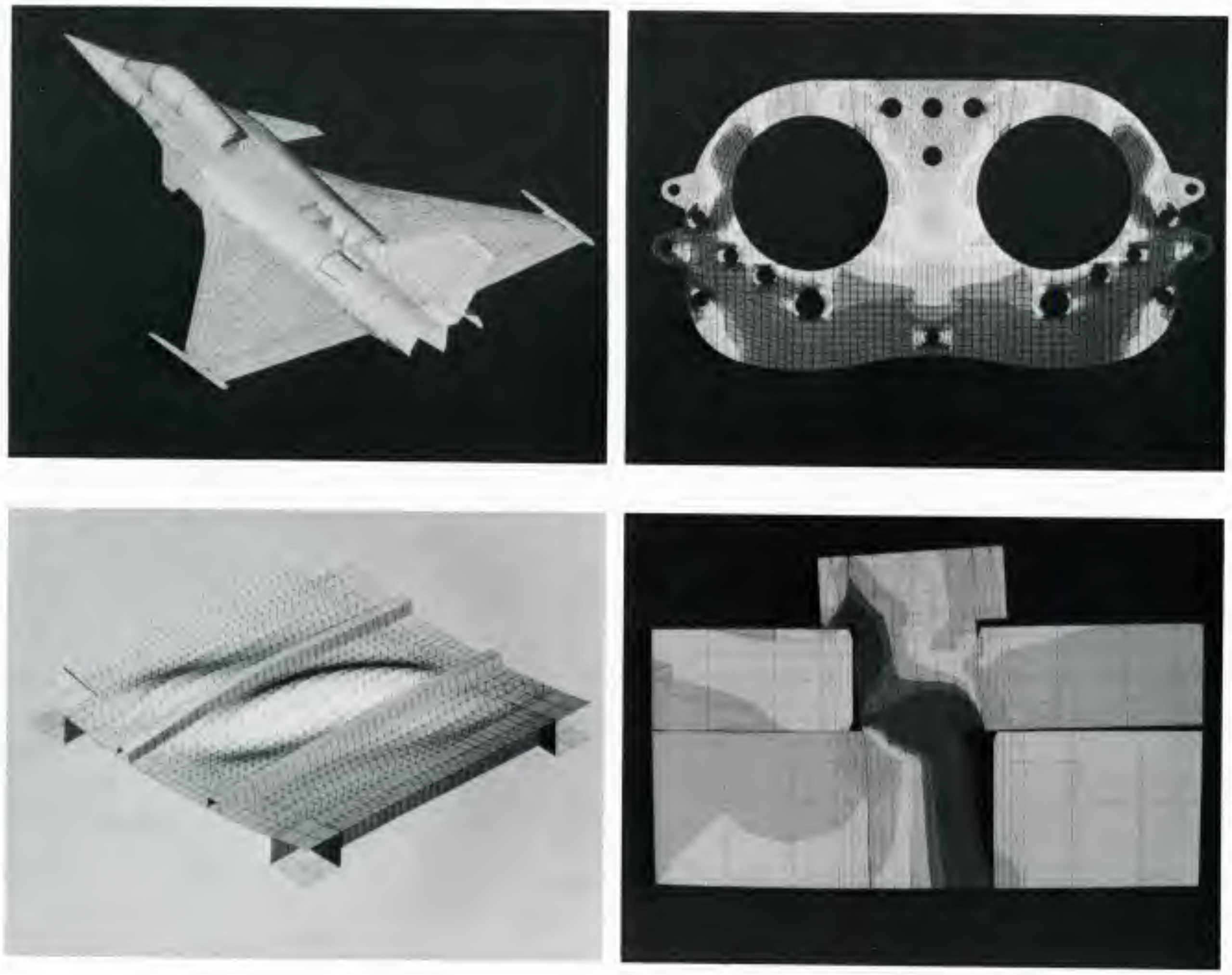


FIG. 36 - USE OF FINITE ELEMENT CODE "ELFINI" ON RAFALE

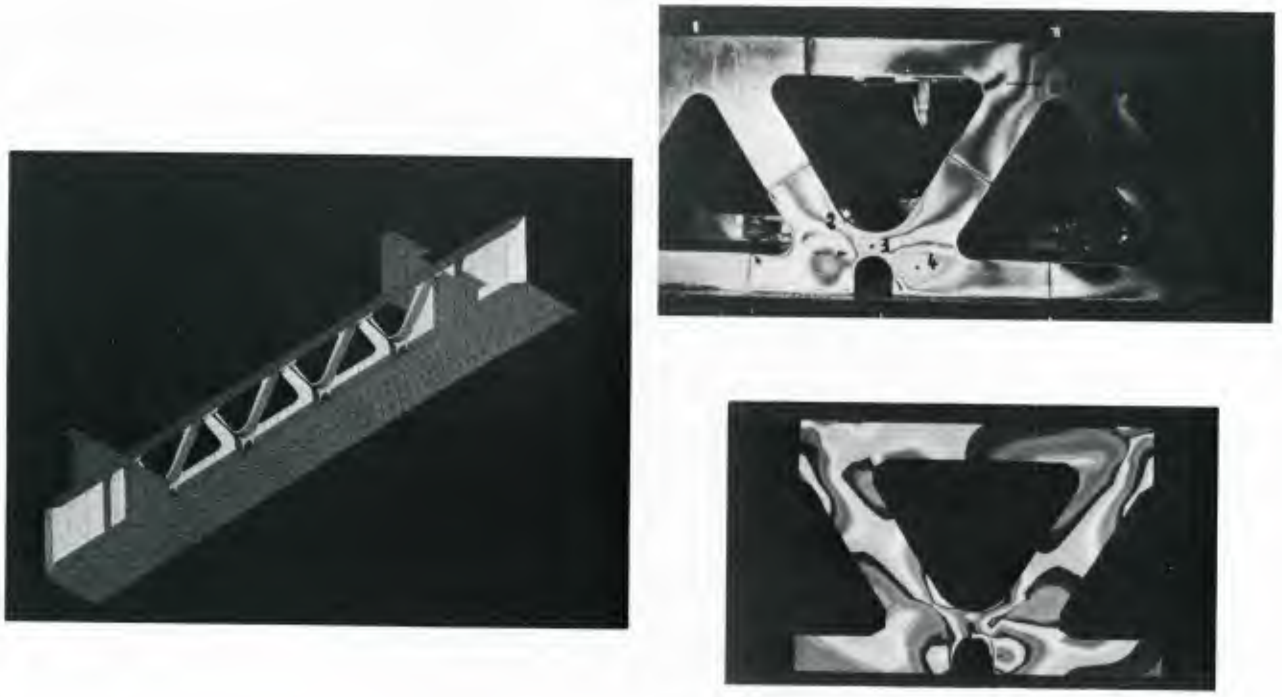


FIG. 37 - STRUCTURE - COMPARISON BETWEEN TEST AND COMPUTATION

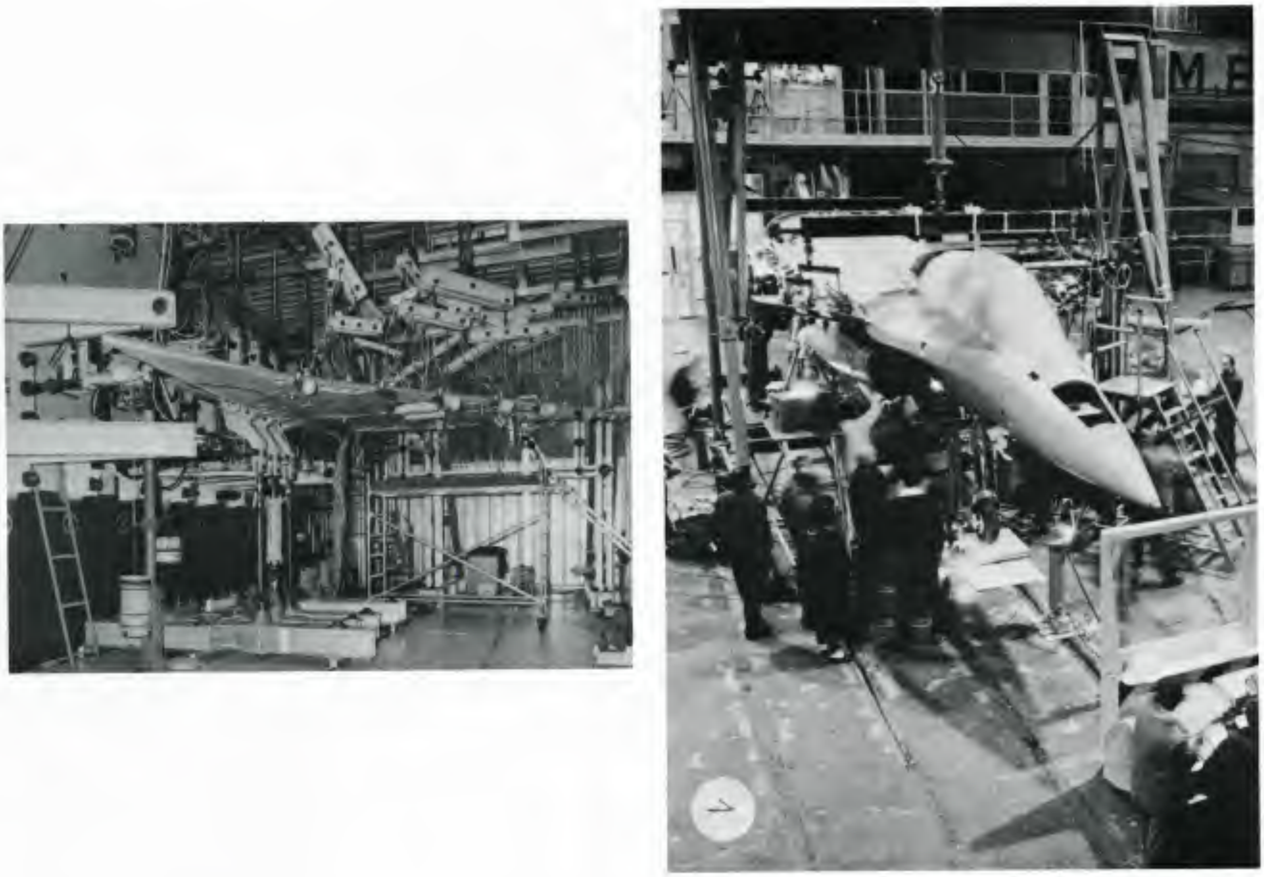


FIG. 38 - STRUCTURAL TESTS

FIG. 39 - SIMULATORS

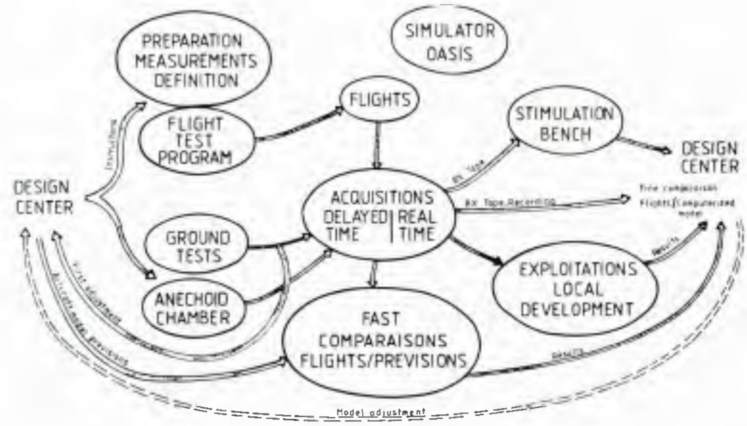


FIG. 40 - FLIGHT TEST ORGANIZATION

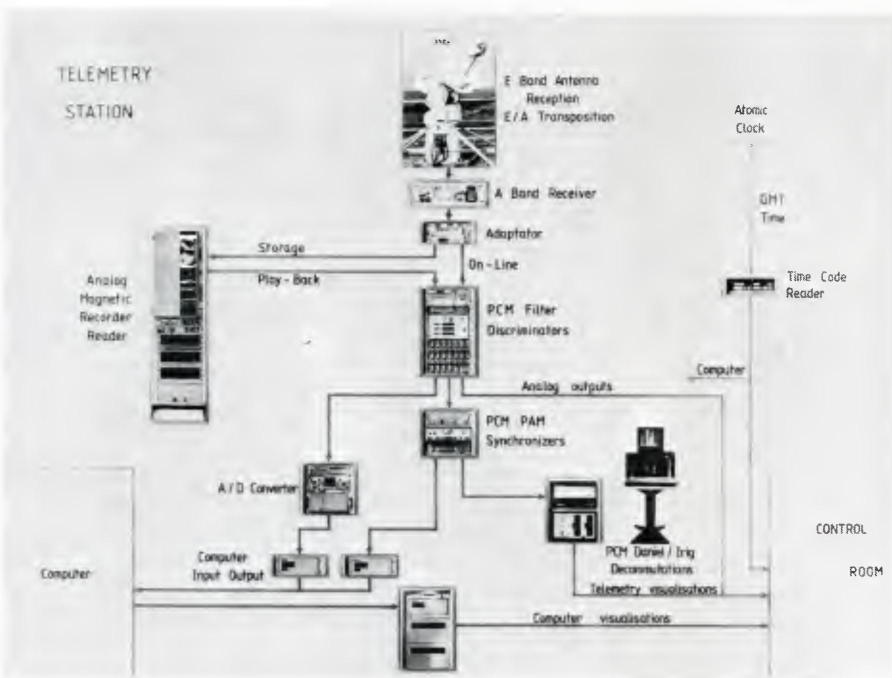


FIG. 41 - FLIGHT TEST SYSTEM

AIRCRAFT

RAFALE DEMONSTRATOR

ENGINE

M88 DEMONSTRATOR

RADAR

- RACAAS DEMONSTRATOR
- ANTILOPE FUNCTIONAL MOCK-UP
- PRELIMINARY DEVELOPMENT OF MULTI-TARGET FUNCTION

MISSILE

PRELIMINARY DEVELOPMENT
OF MICA LAUNCHING

FIG. 42 - THE RAFALE PROGRAMME DEMONSTRATORS

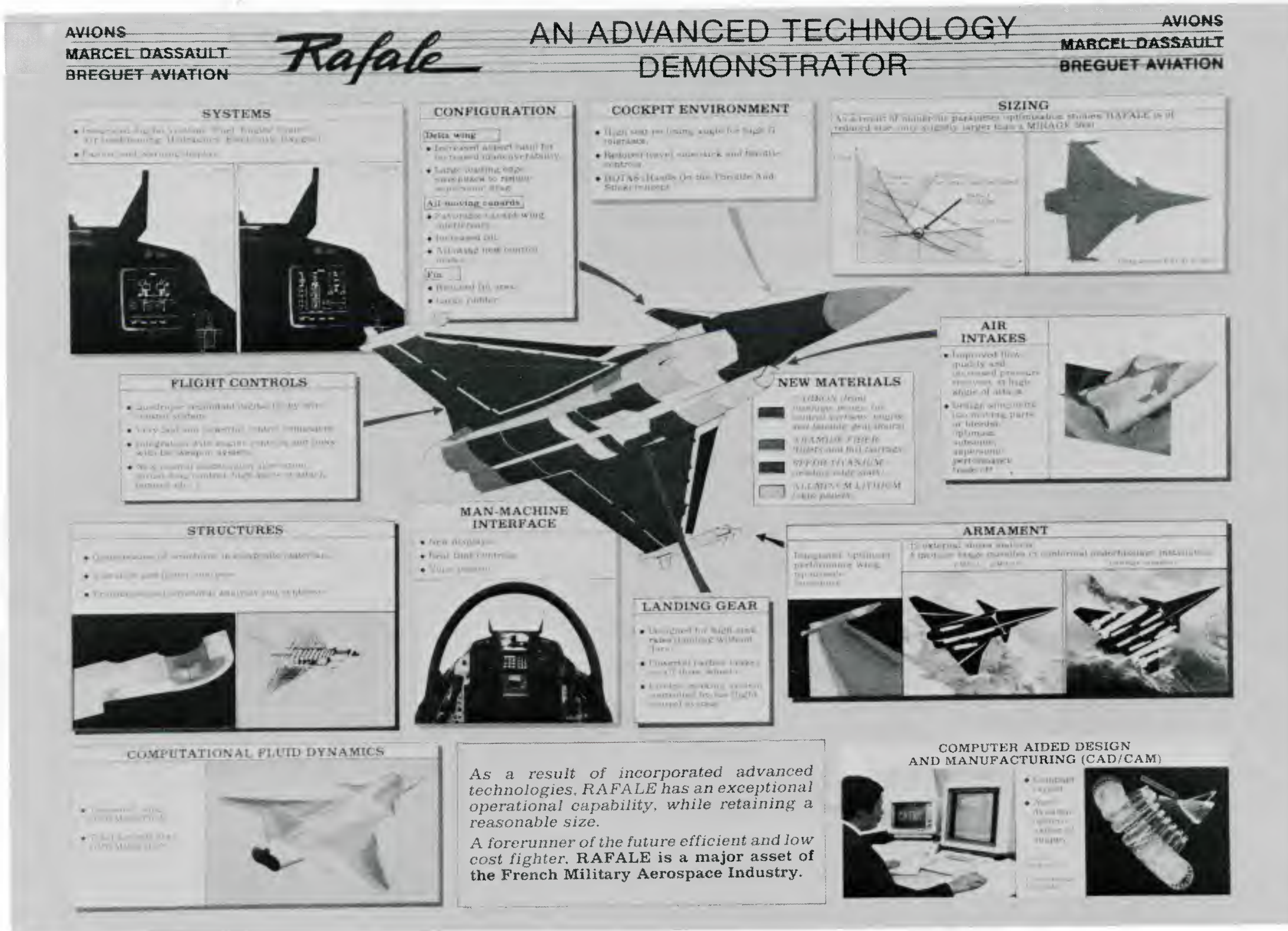


FIG. 43 - RAFALE : AN ADVANCED TECHNOLOGY DEMONSTRATOR

- 1_{st} FLIGHT : 4_{th} JULY 86 - M=1.3 / 36000 FT
- M 1,8 AND LOAD FACTOR=8 g AT THE 6_{th} FLIGHT — 17_{th} JULY 86
- 98 FLIGHTS / 86 HOURS
- M 2 AT THE 93_{rd} FLIGHT — 4_{th} MARCH 87
- FLIGHT ENVELOPE EXPLORED : M = 2 / 600 KTS / 47000 FT
- LOAD FACTORS SUSTAINED : + 9 g / — 2 g
- A o A : 31°
- APPROACH SPEED : 125 KTS
- MINIMUM SPEED : 100 KTS
- FULL DEFLECTION IN ROLL MANŒUVRE WITH RPU
- EXCELLENT AIR INTAKES BEHAVIOUR
- VERY GOOD JUDGMENT BY THE PILOTS ON THE NEW COCKPIT
- 8 PILOTS HAVE FLOWN THE AIRCRAFT
  - 3 FROM THE SOCIETE AMD-BA
  - 2 FROM FLIGHT TEST CENTRE
  - 2 FROM THE FRENCH AIR FORCE
  - 1 FROM NAVAL AERONAUTICS
- MAIN COMMENTS OF OFFICIAL PILOTS :

— AFTER THE 11 th RAFALE FLIGHT (FIRST FLIGHT BEING DONE BY AN OFFICIAL PILOT) : "GENERALLY SPEAKING, ON THE ISSUE OF THE FIRST FLIGHTS ITS QUALITIES AND ON THE WHOLE ITS TECHNOLOGICAL INNOVATIONS GIVE THE IMPRESSION OF A VERY BRIGHT, OUTSTANDING AIRCRAFT"

(FLIGHT TEST CENTRE)

— THEN, FOLLOWING THE ASSESSMENTS BY OPERATIONAL PILOTS : "... POWERFUL AIRCRAFT, MODERN AND WELL SHAPED... EASY TO FLY... QUICK FAMILIARIZATION"

(FRENCH AIR FORCE)

"THE WORK THAT HAS BEEN DONE , SHOULD ALLOW TO DESIGN AN ACT/ACM OF FIRST COMPETITIVE CLASS. THERE IS NOT ANY DOUBT ABOUT THE POSSIBILITY OF THE "NAVALISATION" OF THE RAFALE

(NAVAL AERONAUTICS)

FIG. 44 - RAFALE DEMONSTRATOR - FLIGHT TESTS RESULTS (MARCH 87)

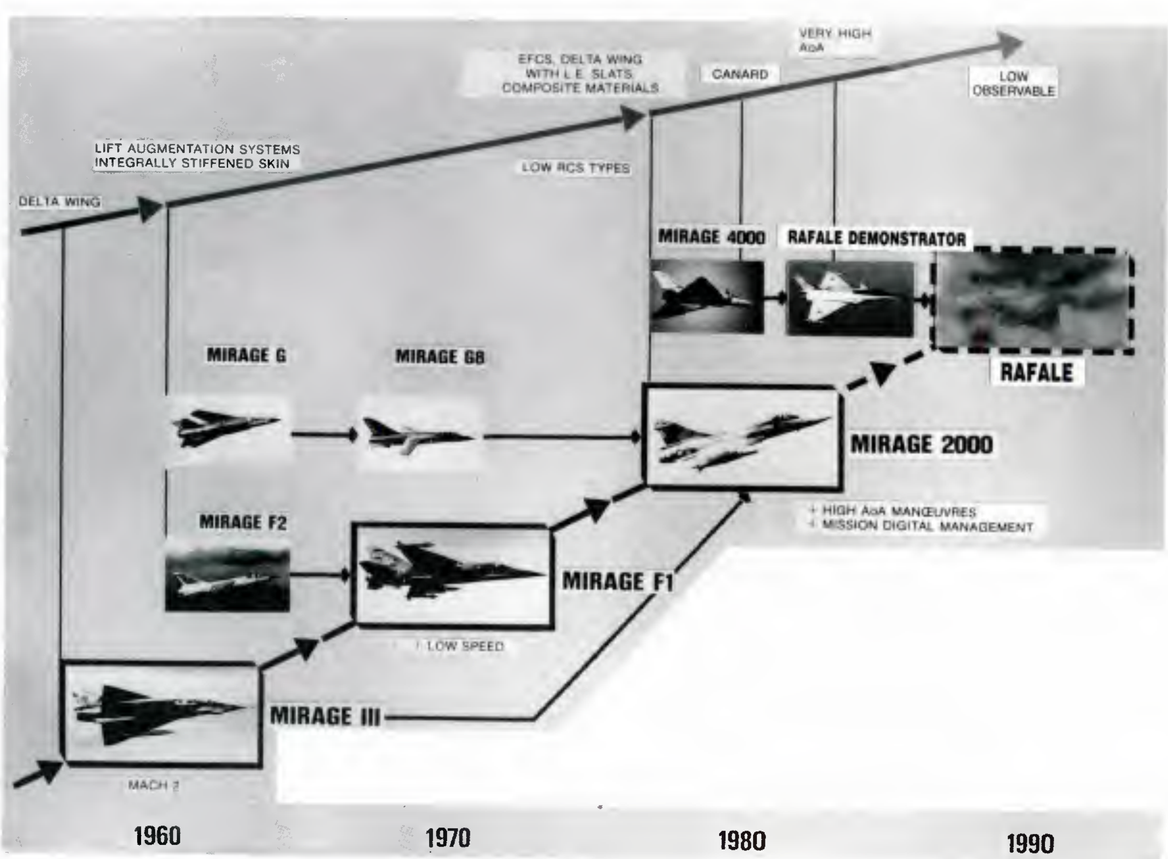


FIG. 45 - A FAMILY OF COMBAT AIRCRAFT

DESIGN OPTIMIZATION OF FIGHTER AIRCRAFT

by
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P. O. Box 516
St. Louis, Missouri 63166

SUMMARY

The explosion of digital computation capability over the last 30 years has transformed the military aircraft design process, and provided unprecedented opportunity for true optimization of selected configurations prior to production commitment. To date, this revolution has worked primarily to reduce risk in aircraft development. Today's new aircraft flies as expected, without unforeseen handling quirks or instability, and exploration of most, if not all the flight envelope is possible on the first flight. Digital flight simulation, sophisticated wind tunnel test techniques, and performance, structural and thermal modeling all combine to elevate confidence in a new design to a very high level. So long as the rate of technology advancement and capability increase required in each succeeding new aircraft remain high, elevated confidence and reduced risk will continue to be the primary effects on high performance aircraft design. Another, as yet unrealized benefit is an enormous potential improvement in productivity and efficiency, and therefore cost, of the aircraft design and manufacturing process.

This paper is intended to provide insight into the modern aircraft development process from the perspective of a designer and builder of high performance military fighters, McDonnell Aircraft Company. The processes and capabilities described are not achieved without growing pains and numerous lessons of experience.

THE DESIGN PROCESS

The fighter aircraft design process begins with a requirement, which may be explicitly stated in great detail in a request for proposal, or may be only a vague perception of need by the designer. In either case, the designer must know the purpose for the new aircraft before he can begin to design it. Is the aircraft needed for interception of Mach 2 threats at maximum distance, or is it to be used to achieve air superiority against great numbers of highly maneuverable but subsonic hostile aircraft? Or, will it be used for both purposes? Must it be able to carry large quantities of air-to-ground ordnance deep into enemy territory and then fight its way back unescorted? Will it be land based, or operate from an aircraft carrier? Two factors are predominant in establishing the requirement and the response: these are the threat, and available technology. Once the threat and requirements are understood, then the response can be tailored from existing and emerging technologies, and the designer can get on with the business of creating a new aircraft.

The fighter aircraft design process is a series of compromises. A variable sweep wing provides optimum wing geometry throughout the flight envelope, but at the expense of weight, complexity, and cost. If the aircraft is to be used for both air-to-ground ordnance delivery and air superiority, compromises are required between air-to-ground range and payload, and air-to-air performance. Fixed inlet geometry is simple and lightweight, but limits maximum speed. These configuration decisions, and hundreds more, have interacting effects, often very complex. Prior to availability of the high speed digital computer, all these variables, and their interacting effects had to be dealt with manually. The number of alternate configurations, and individual details within a given configuration which could be considered for a new aircraft design were limited by the time and manpower available. Today's designer is constrained only by the limits of his own imagination and available resources and technology.

COMPUTER GRAPHICS DESIGN INTEGRATION

After assimilating the mission and performance requirements, and selecting rough configuration details (variable vs. fixed inlets; wing sweep; crew size; radar antenna size; single vs. twin vertical tails, etc.) the designer begins to draw the aircraft on a computer graphics terminal.

The computer graphics software contains algorithms and parametric relationships for such things as crew station volume, over the nose visibility, landing gear location, etc. If the aircraft is to be carrier based, the software contains provisions for deck spotting factors, which influence overall length and wing fold locations, catapult clearances, and other factors peculiar to shipboard operation.

The wing is located longitudinally for balance, and vertically for compatibility with the engine and inlet system. Parametric relationships are used to size and locate the horizontal and vertical tails to satisfy stability and control criteria. Available fuel volume is determined and compared to preliminary estimates needed for required missions. Volume is also provided for avionics, hydraulics, electrical, and flight control systems along with associated wiring, plumbing, and actuators.

The result of this process is a 3-view aircraft drawing, a set of geometric characteristics, and plots of wetted area and cross-sectional area distributions. The computer graphics aircraft contour definition may also be used for numerical controlled machining of wind tunnel models.

Performance of the "as drawn" configuration is computed, and compared with mission requirements. This process is repeated until the configuration exhibits the desired performance, size, supportability, and life cycle cost. Computer graphics techniques not only allow the designer to evaluate many alternatives efficiently, but also assist him in visualizing the operational environment. This chart shows characteristics of the engine nozzle plume, and this one depicts aircraft skin temperature with a color code.

Once a candidate configuration emerges from the graphics integration process, a Computer Aided Design Engineering program (CADE) is used at McDonnell to further refine the configuration. CADE considers aerodynamics, weight, propulsion, configuration and cost to perform parametric analyses, trade and sensitivity studies, and comparisons of alternate configurations. Examples are:

- Cost vs. gross weight
- Manuever performance vs. wing loading
- Effects of wing sweep angle
- TOGW vs. maneuver performance
- Fuel load vs. engine size
- Wing area vs. cruise rating
- Dash radius vs. drag increments
- Maneuver performance vs. small thrust changes
- Scaling alternative configurations to same performance, TOGW, fuel load, etc.

CADE is a gross tool, not a detail design aid.

WIND TUNNEL AND SIMULATION

The wind tunnel and manned flight simulator are used in parallel with these design studies to select, refine and integrate design details. The wind tunnel is a powerful tool in the development and optimization of an aircraft configuration. Computation capability advances have enhanced ability to attain more accurate, better visualized data faster than before. Captive trajectory techniques allow store separation characteristics to be determined by driving a sting-mounted store closed loop, from loads produced by the local flow field surrounding an aircraft model.

Another technique allows computer graphics presentation of local flow field pressure gradients as multi-colored contour plots as an aid to flow visualization. In this technique, rake mounted pressure probes are driven in 1/10 in. increments in the model area of interest by a stepper motor. Pressure data is taken at each position. A software program converts the data to engineering units and computes pressure recovery ratio. The contour plot shown illustrates the pressure field adjacent to the F-18 vertical tail caused by vortices originating at the wing-fuselage intersection. Bands of constant color represent areas of constant pressure. This type of plot involves about 45,000 data points, and requires about 10 minutes processing time on an Sel 32/75 computer.

The need to simulate manned flight, on the ground, without the risk and expense of flight test, is as old as manned flight itself. Realistic, real-time, man-in-the-loop flight simulation became a powerful force in the design process at McDonnell in the late 1960s, and was first applied on the F-15 program.

Simulation is very effective in early verification of design concepts, identification of potential operational problems, and identifying areas needing further development. In addition, it is useful in integration and software validation, tactics and mission development, support of flight testing, accident investigation, training and marketing. It is an excellent method for attaining customer involvement and participation as a design progresses, and for obtaining consensus in selection from multiple alternatives.

Simulation provides capability for real time, man-in-the-loop configuration evaluation, with a high fidelity crew station utilizing actual cockpit displays, realistic flight cues, and interactive targets and threats.

During the conceptual design phase existing facilities are usually modified to represent the concept being investigated. These preliminary simulations provide sufficient realism to aid the designers in discarding bad ideas and in refining good ideas. Evaluations by management, and customer or potential customer personnel are also used in this phase. Here's an example of a conceptual phase simulator cockpit.

After the basic aircraft configuration has been chosen and development is underway, a more detailed cockpit simulation is equipped with a hi-fi software model for mission simulation throughout the flight envelope. Sophisticated imagery is employed to provide realism. Customer design reviews are very effective with these simulators.

During systems integration and validation of a nearly mature configuration, a simulation cockpit is built with prototype or production controls and displays, and mission and flight control computers. This very realistic simulator is used to evaluate pilot workload, validate software, optimize cockpit layout, and for pilot training. Here's an example of this type of simulator. Simulation is also very effective in developing and training pilots in weapons tactics.

CAD/CAM

When detail design is started computer graphics allows escape from the 2-dimensional bonds of the drafting board into the real 3-dimensional world, where spatial relationships are easily perceived and accurately portrayed. Required envelopes and clearances for moving parts, such as control surfaces, are readily displayed. One of the most significant applications of this 3-dimensional tool in use at McDonnell is the electronic mockup, which can replace the traditional tube and cable mockup used to develop routing for hydraulic tubing, electrical wire bundles, control cables, and their supporting bracketry. This technique has been used recently, with great success, during design of the forward fuselage for the TAV-8B Harrier trainer. Advantages over the conventional shop mockup include not only a more efficient, but also a more accurate engineering design process. Changes during assembly of the first aircraft (which made its first flight on 21 October 1986) have been less than half those experienced with conventional techniques. In addition, elimination of the mechanical mockup will save millions of dollars in development of a typical fighter aircraft.

Design for optimum supportability is assisted by easy visualization of operational factors such as missile loading and clearances in ground revetments.

Perhaps the greatest potential payoff from computer aided design is the availability and use of a common data base by analysts, designers, manufacturing, inspectors and logisticians. All lofted moldline contour definition is a part of this data base. Stress analysts construct finite element models and compute stress distribution with the computer graphics geometry and structural definition data. Machined bulkhead contours are accessed by NC Programmers, and finished parts are inspected to dimensions originating from common data. Maintenance publications and field repair data, including technical illustrations, are all prepared from the same data, enhancing not only accuracy, but promoting a common, understandable language among all users.

FLIGHT TEST

Even though today's newly developed aircraft make their first flights with high confidence that there are no lurking unknowns, we haven't yet reached the point where flight testing can be eliminated. High speed data computation allows critical data to be displayed in engineering units during flight, and hugh quantities of processed data are available within hours after the flight.

VIDEOTAPE - ROLE OF COMPUTER GRAPHICS IN AIRCRAFT DESIGN

CONCLUSION

Today's aircraft designers have a near limitless array of tools for design optimization at each step in the process, and many of these tools also enhance manufacturing and other post-design activity. Some aerodynamic phenomena still elude our ability to model precisely, e.g., flight at extreme angles of attack and spin entry. However, most regimes of flight dynamics can be modeled, and iterated endlessly with multiple variation in configuration details, to produce a truly optimum design for a given requirement <u>if</u> orchestrated effectively by the designer. All the computation power in the world <u>will</u> not compensate for faulty judgment. Garbage in is still garbage out. Effective intuitive judgment and a feel for the sensitivities to the variables being manipulated are essential ingredients unlikely ever to be completely programmed. The human mind will always be the ultimate computer. However, power of the mind can be multiplied a thousand-fold by effective use of computation power now available.

Figure 1.
Threat Trends
SAMs

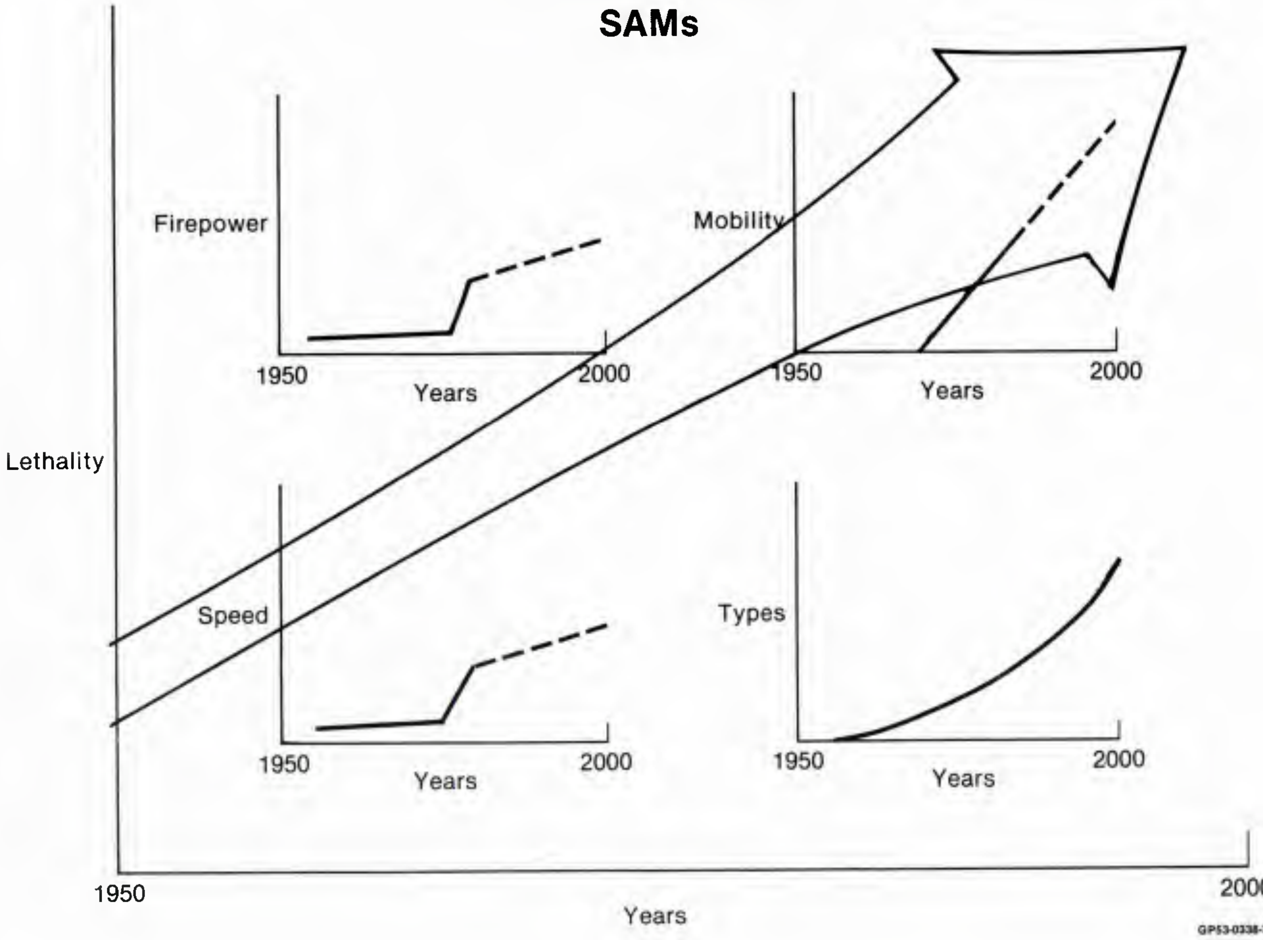
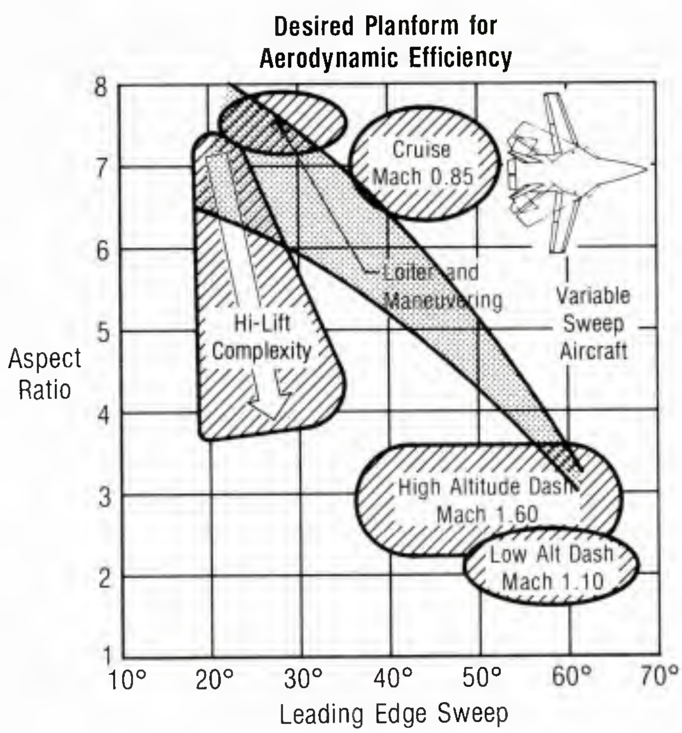


Figure 2.
Wing Planform Studies



	Criteria
• Mach 0.85 Cruise	L/D_{max}
• Loiter	L/D_{max}
• Mach 0.65 Maneuvering	$L/D_{0.8\ CL}$
• Mach 1.6/50,000 ft Dash	$L/D_{50,000}$
• Mach 1.1/S.L. Dash	$C_{D_{min}}$
• Carrier Suitability	ΔW_{wing}

MCDONNELL DOUGLAS CORPORATION

GP53-0338-65

Figure 3.

MATCHING THE CONFIGURATION TO THE REQUIREMENTS

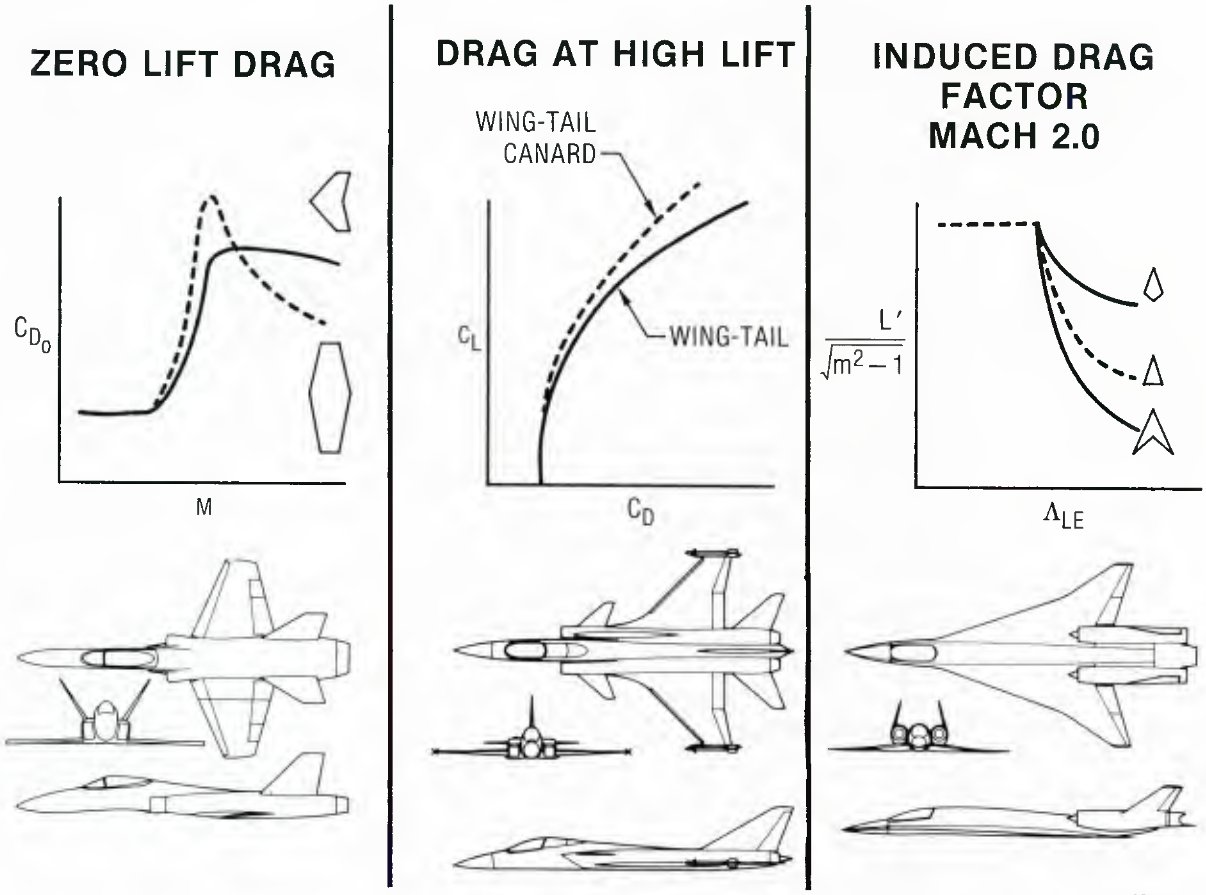


Figure 4.

Computer Graphic Design Integration

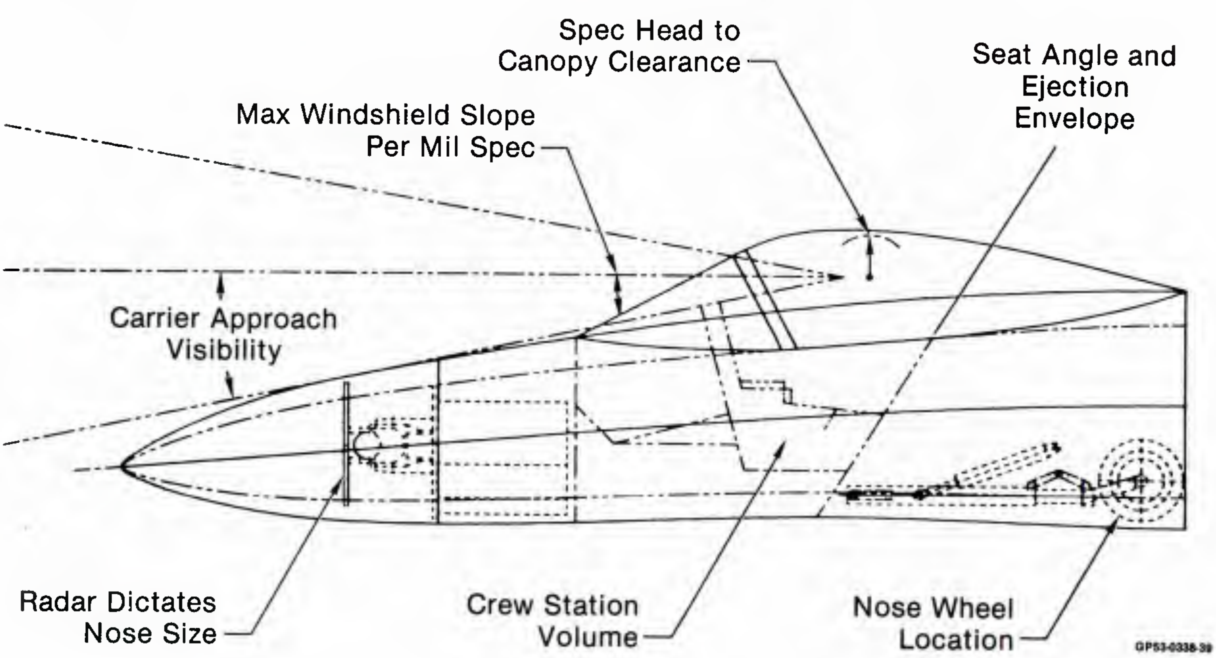


Figure 5.

Computer Graphic Design Integration

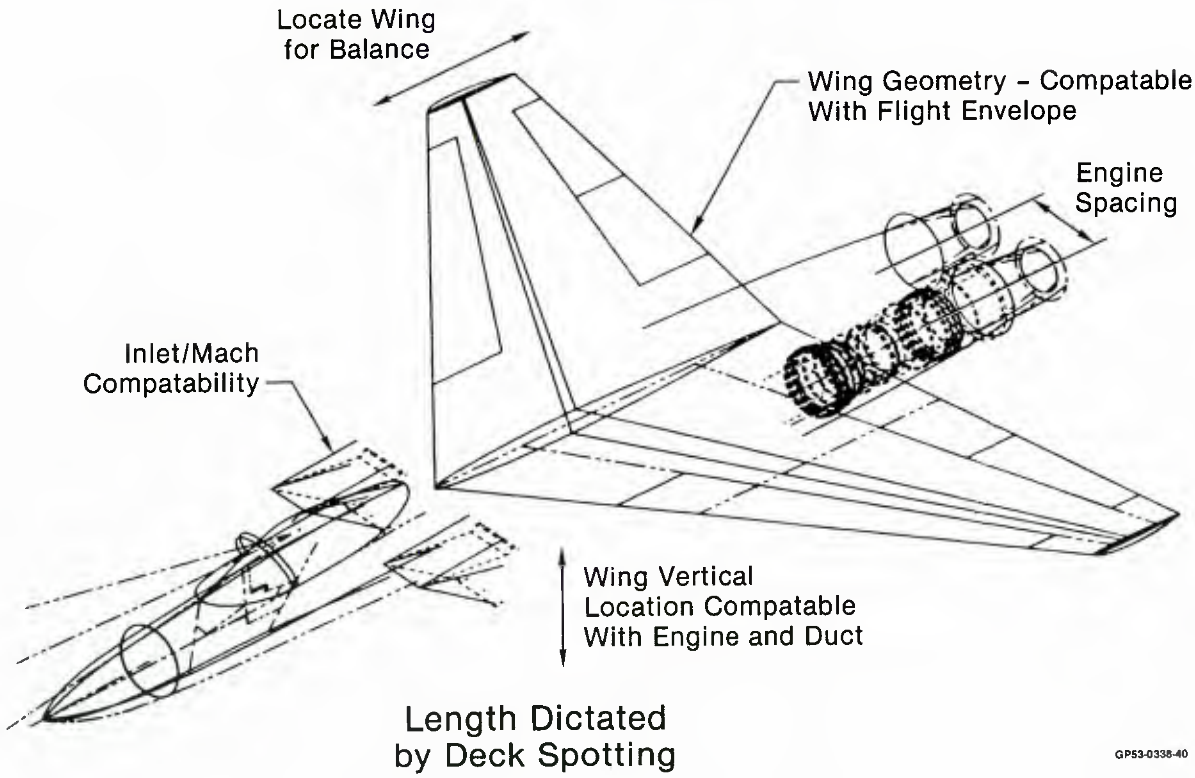


Figure 6.

Computer Graphic Design Integration

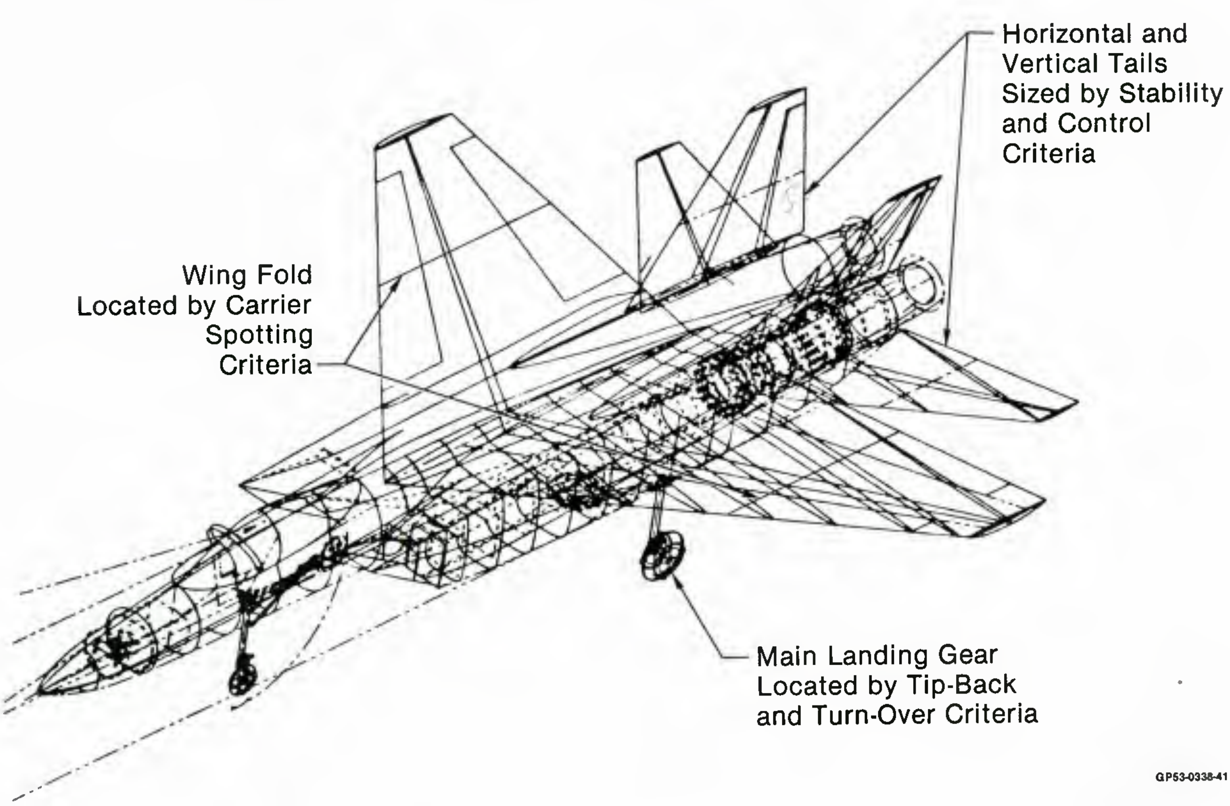


Figure 7.

Computer Graphic Design Integration

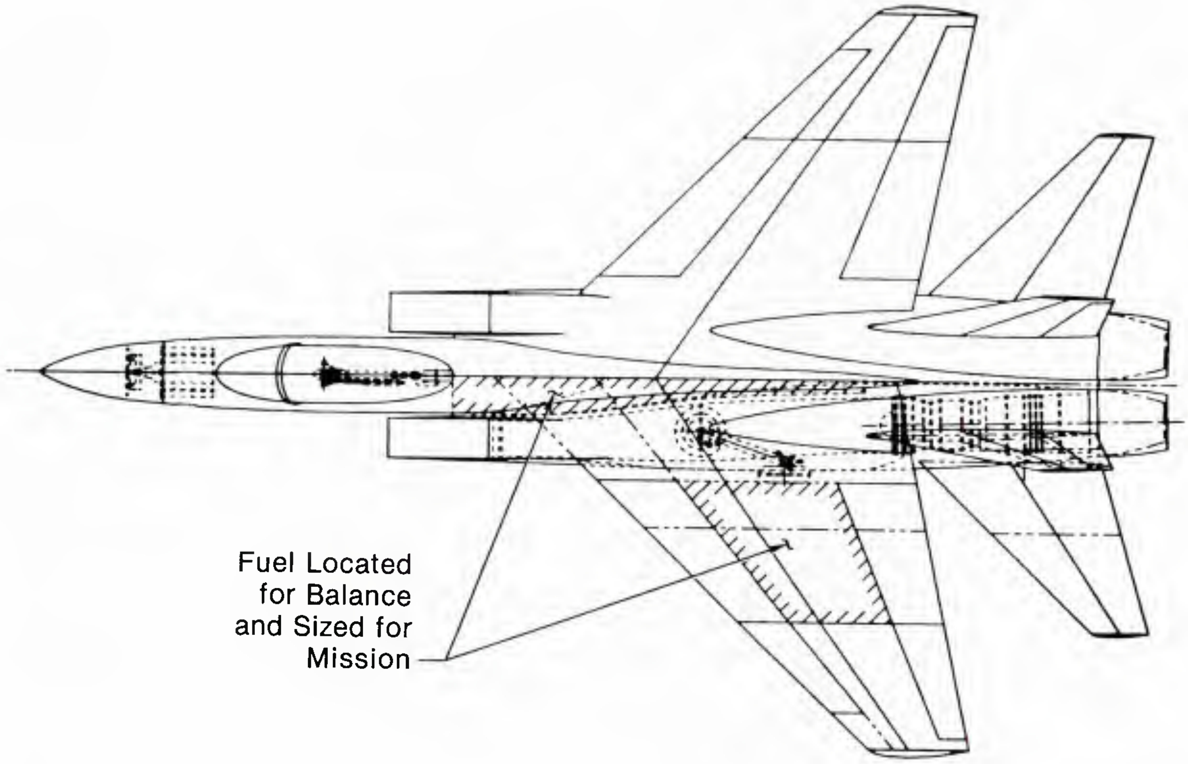


Figure 8.

Computer Graphic Design Integration

Aircraft Three-View

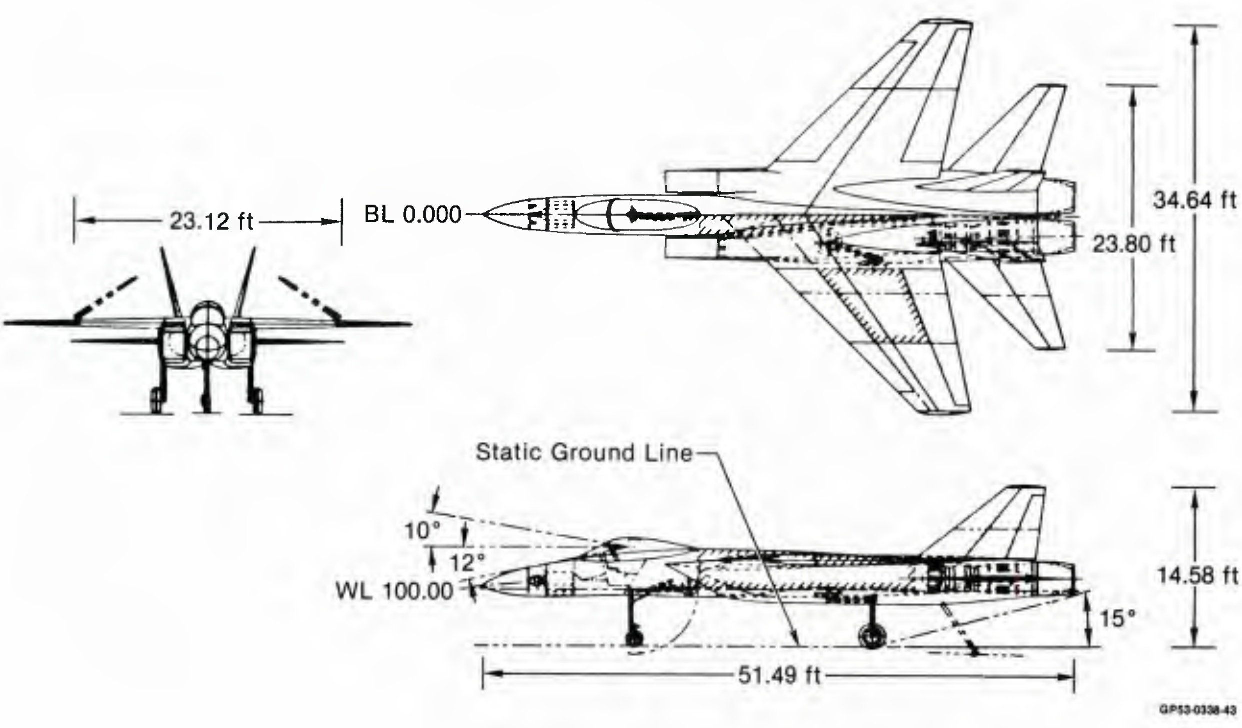


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Figure 9.

Computer Graphic Design Integration

Aerodynamic Characteristics

	Characteristics		
	Wing	Horizontal Tail	Vertical Tail
S (ft^2) Theo	400.000	87.784	92.782
S (ft^2) Expo	261.740	87.784	92.782
Aspect Ratio	3.000	3.000	1.000
Taper Ratio	0.250	0.300	0.300
Ref Span (ft)	34.641	16.228	6.810
1/2 Ref Span (in.)	207.846	97.369	81.724
Root Chord (in.)	221.703	99.865	125.730
Tip Chord (in.)	55.428	29.960	37.719
MAC (in.)	155.192	71.186	89.623
YBAR (in.)	83.138	39.946	33.528
LE of MAC (in.)	330.202	521.203	492.431
FS 1/4 MAC (in.)	369.000	539.000	514.594
BL/WL MAC (in.)	83.138	84.207	166.825
Sweep of LE	45.000	45.000	50.000
Airfoil CR	64A0006	Bi-Convex	64A0005
Airfoil CT	64A0004.2	Bi-Convex	64A0003.5
T/C Root	0.060	0.060	0.050
T/C Tip	0.042	0.030	0.035
Incidence			
Dihedral			15.000
Toe			1.500
Twist			
Camber			
Static Margin (%)			

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Figure 10.

Computer Graphic Design Integration

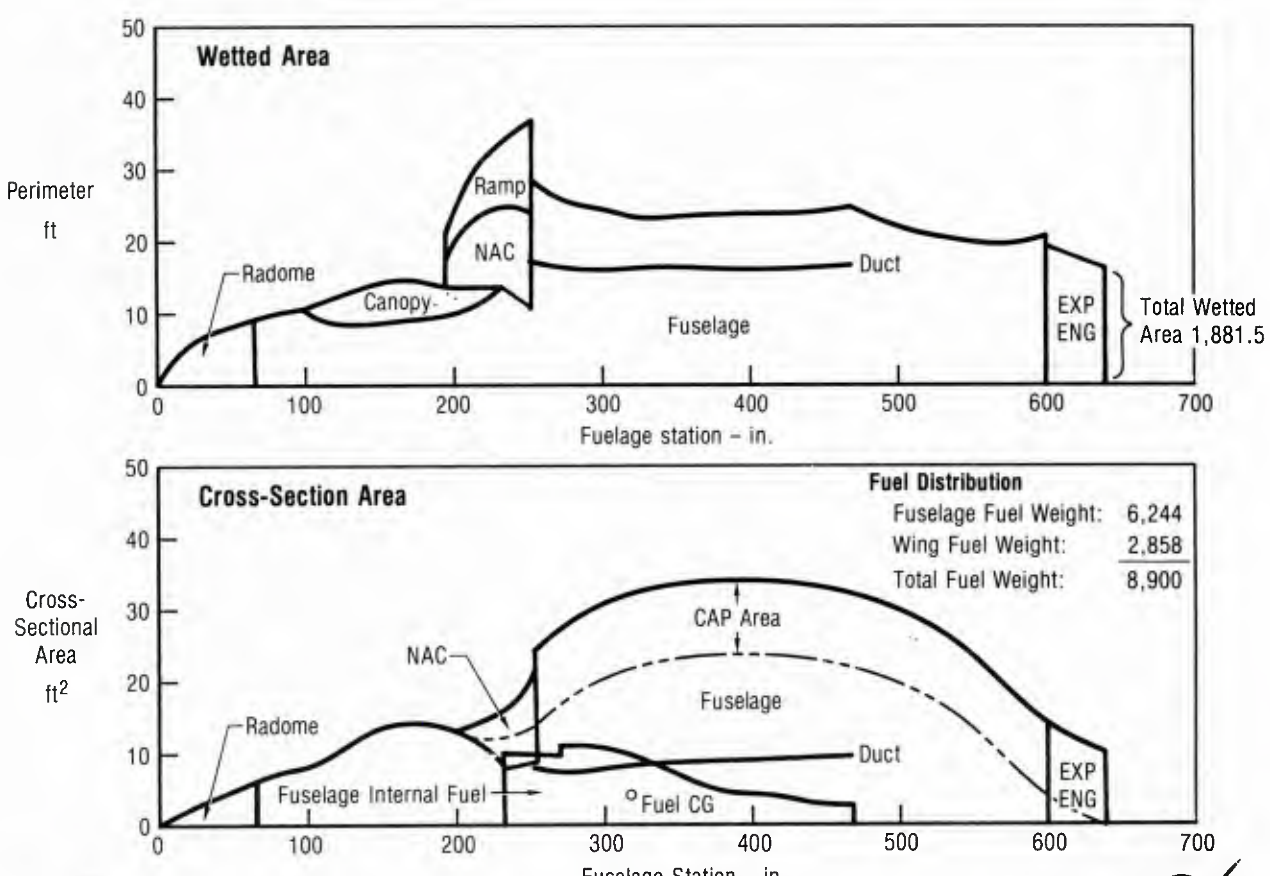

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Figure 11.
Configuration Evaluation

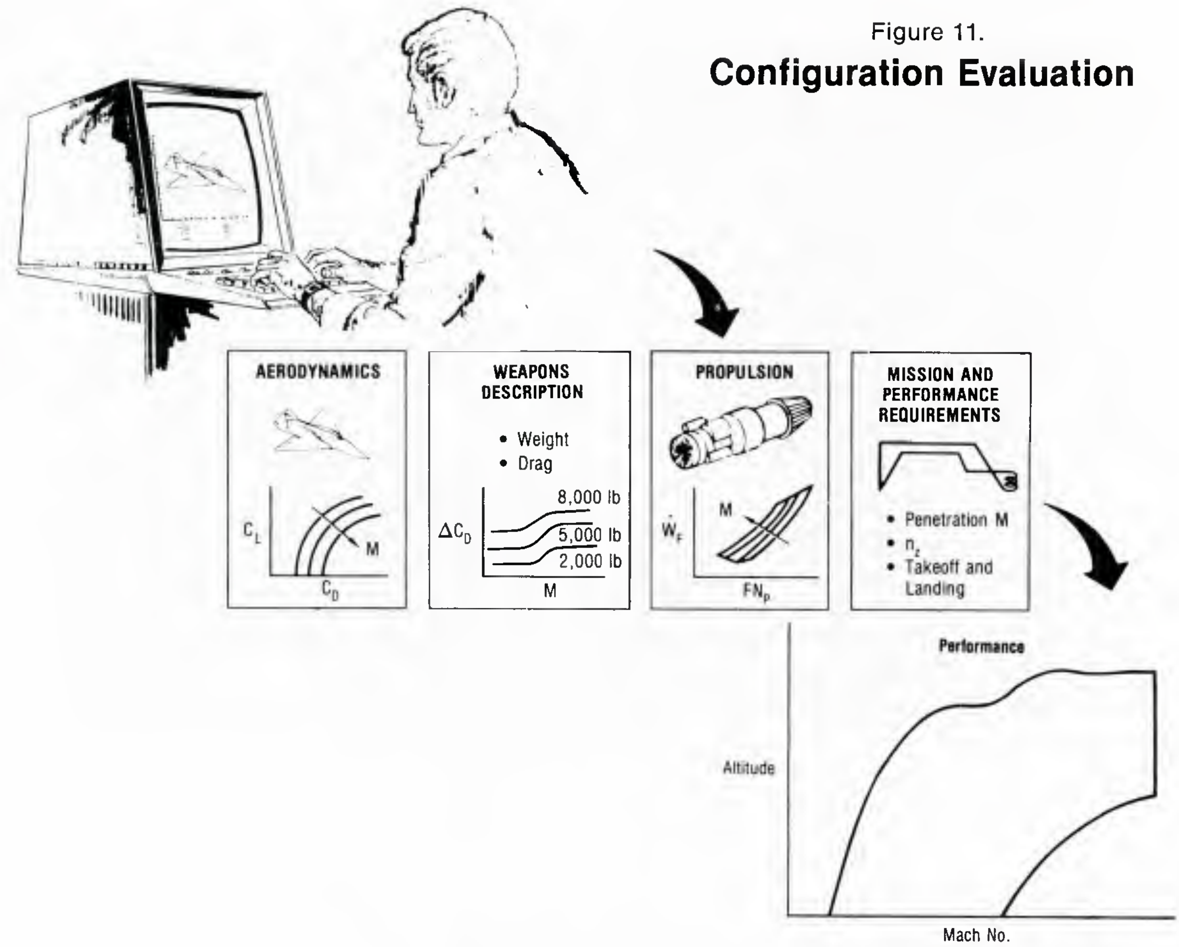

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Figure 12.

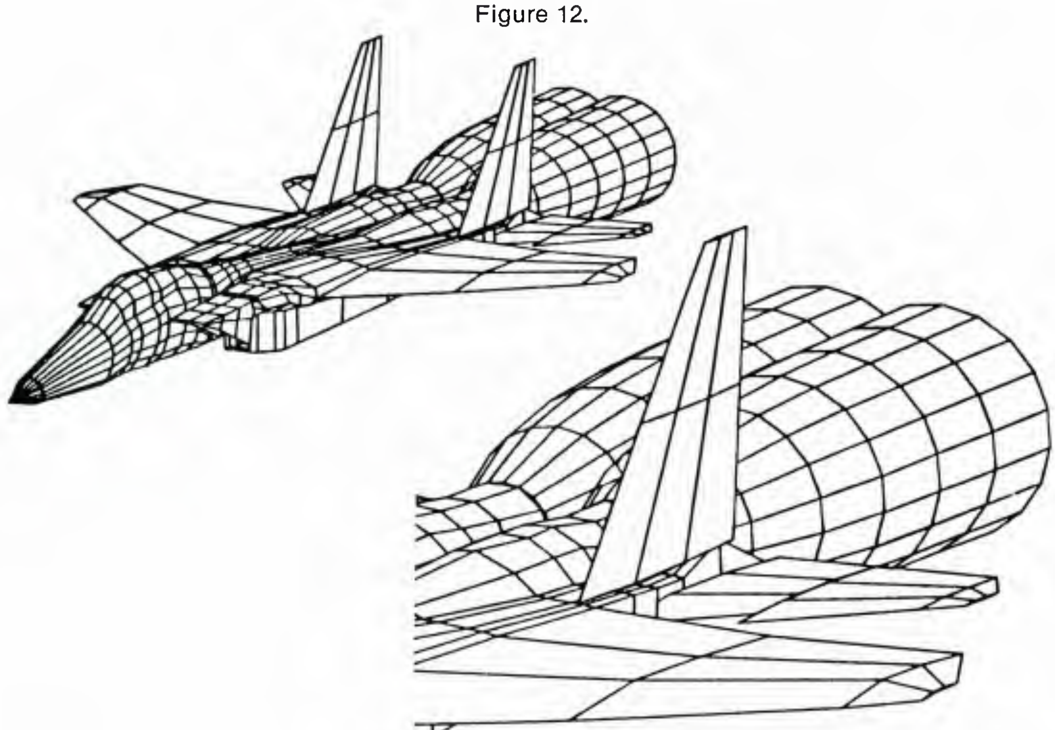

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Figure 13.

Figure 14.

CADE Procedure

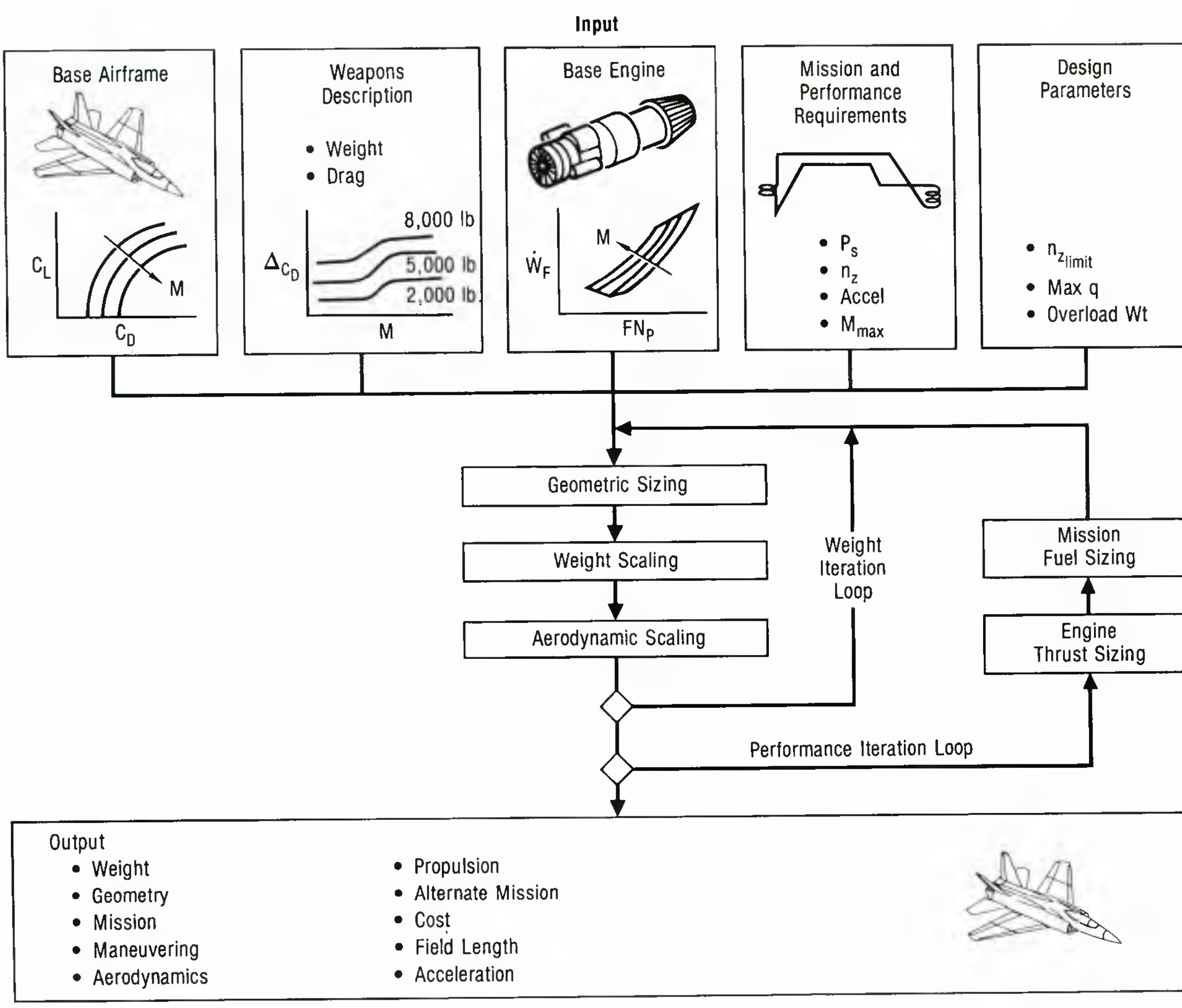

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Figure 15.

Effect of Maneuvering Performance on Aircraft Size

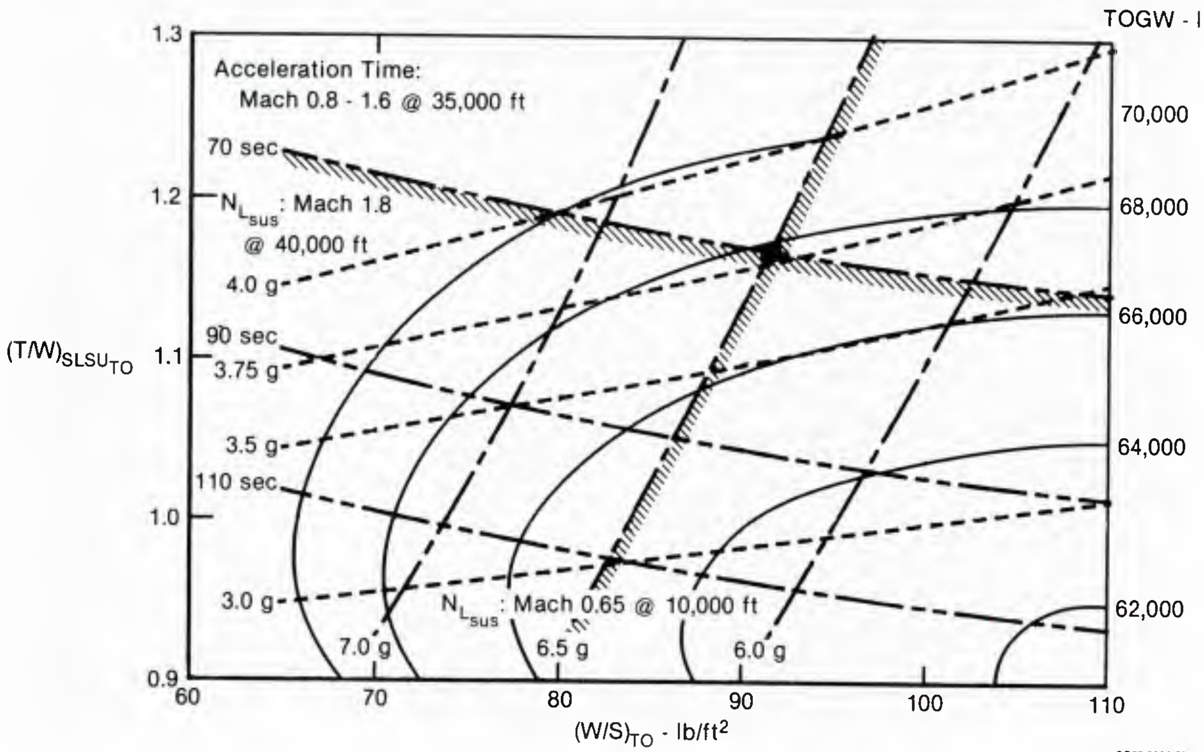

Figure 16.

Wing Parametric Studies

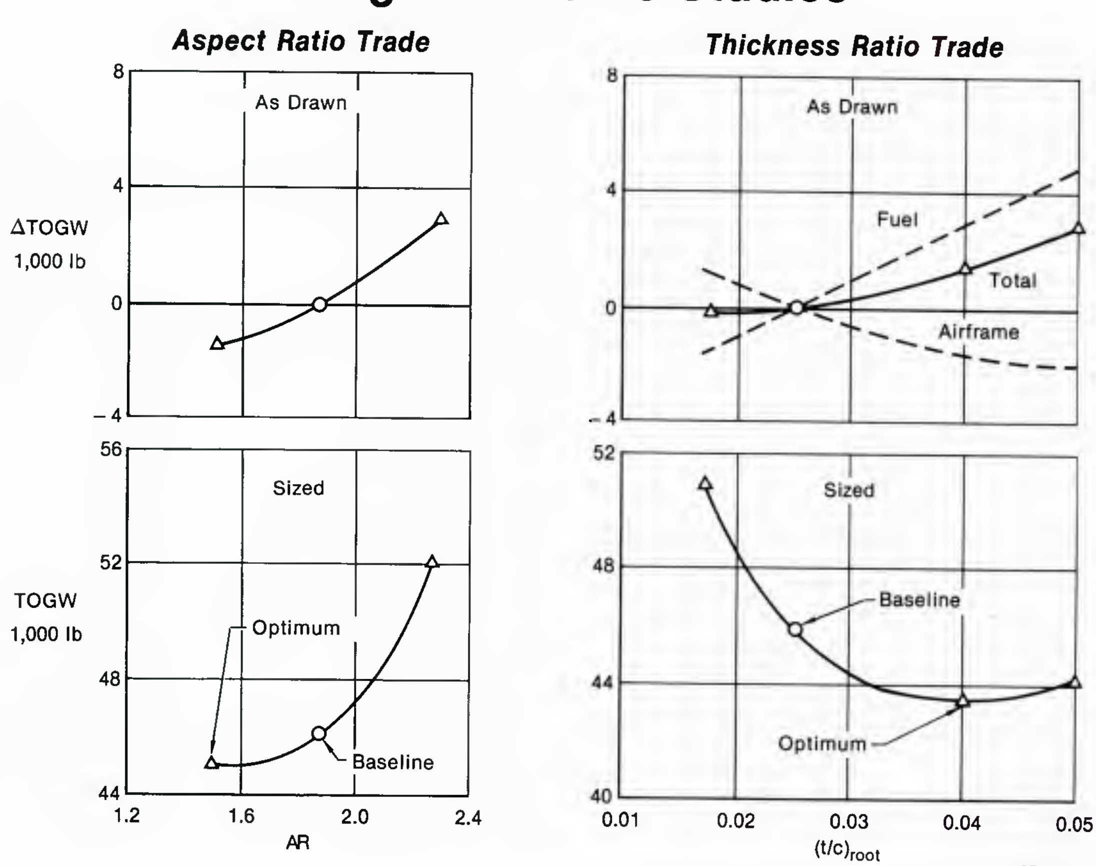

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Figure 17.
High Angle-of-Attack Testing

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Figure 18.

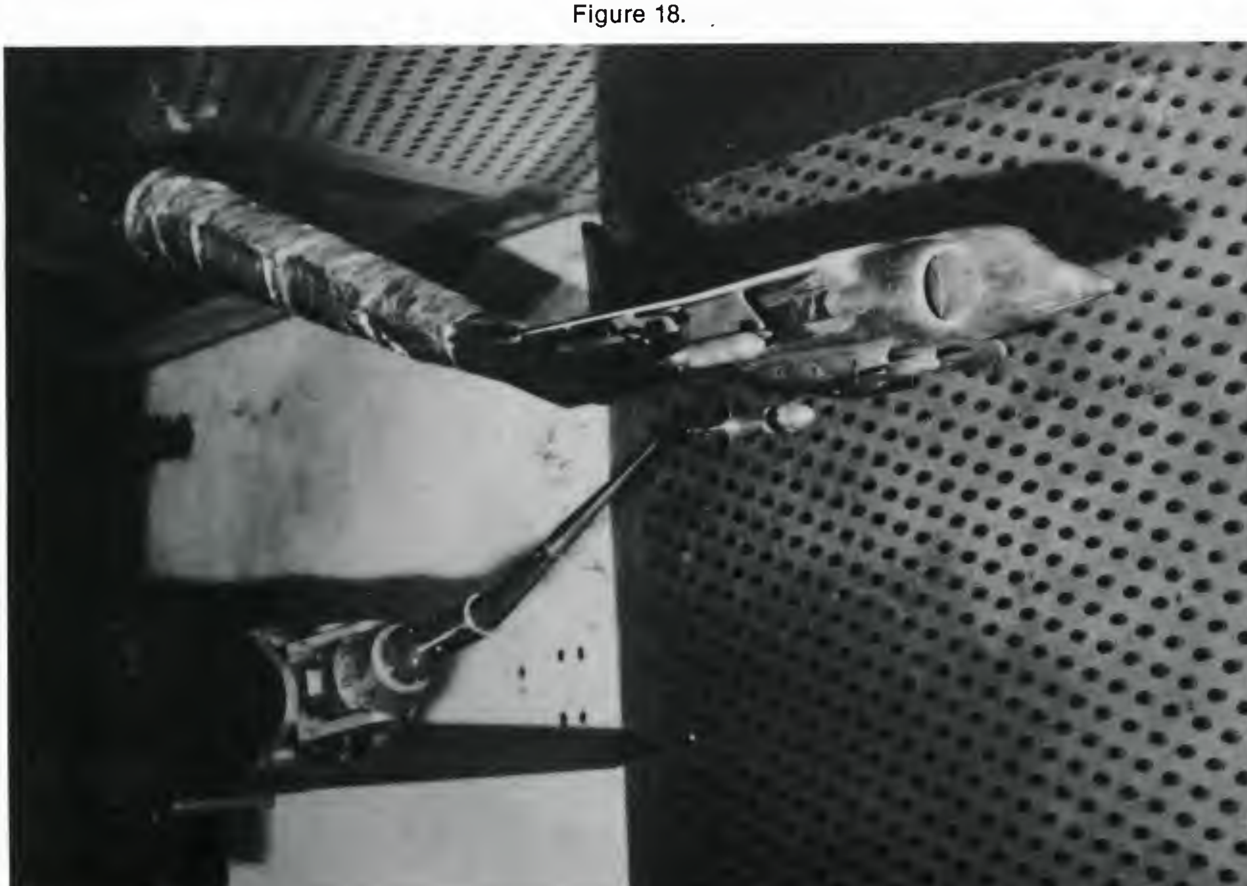

Figure 19.

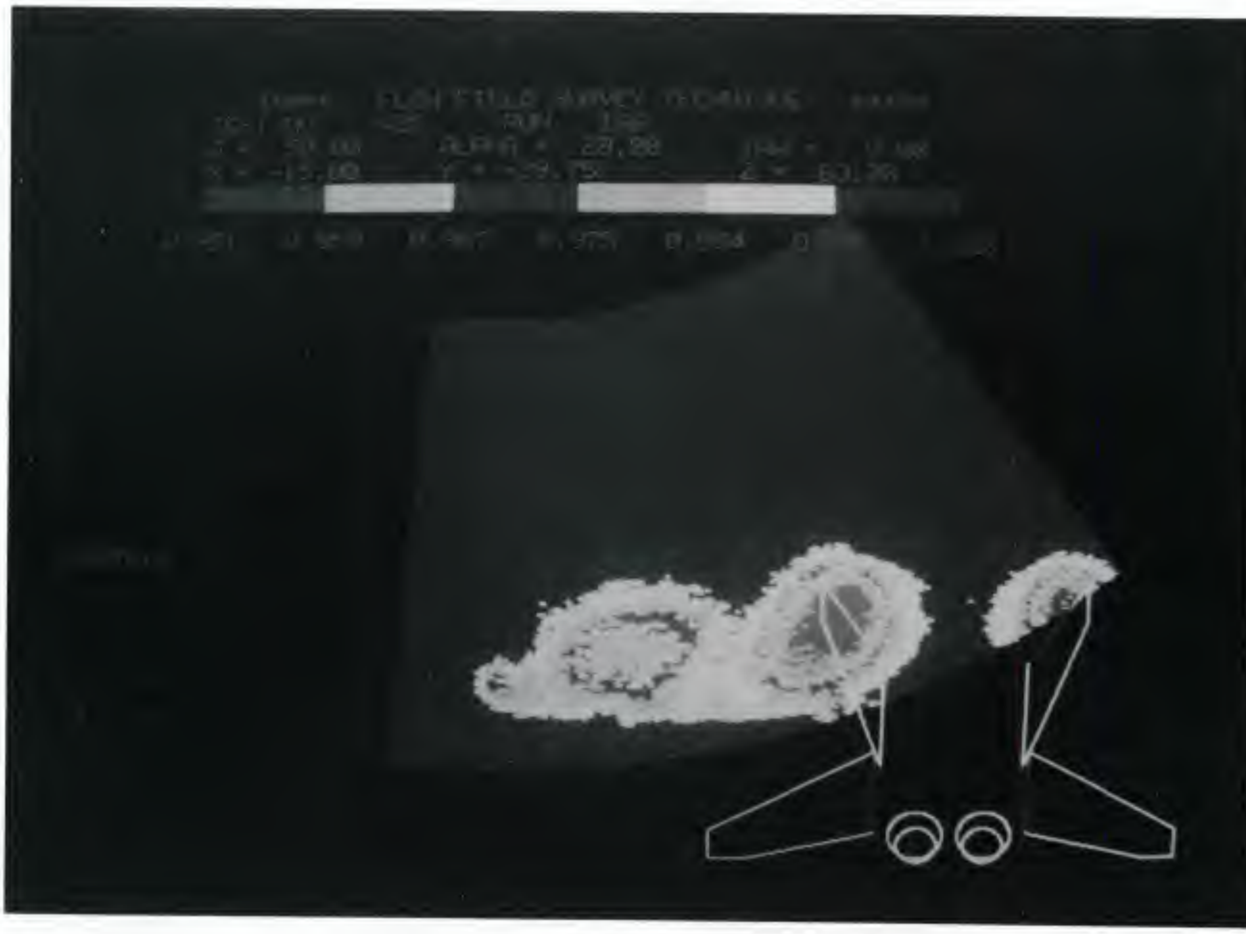

Figure 20.

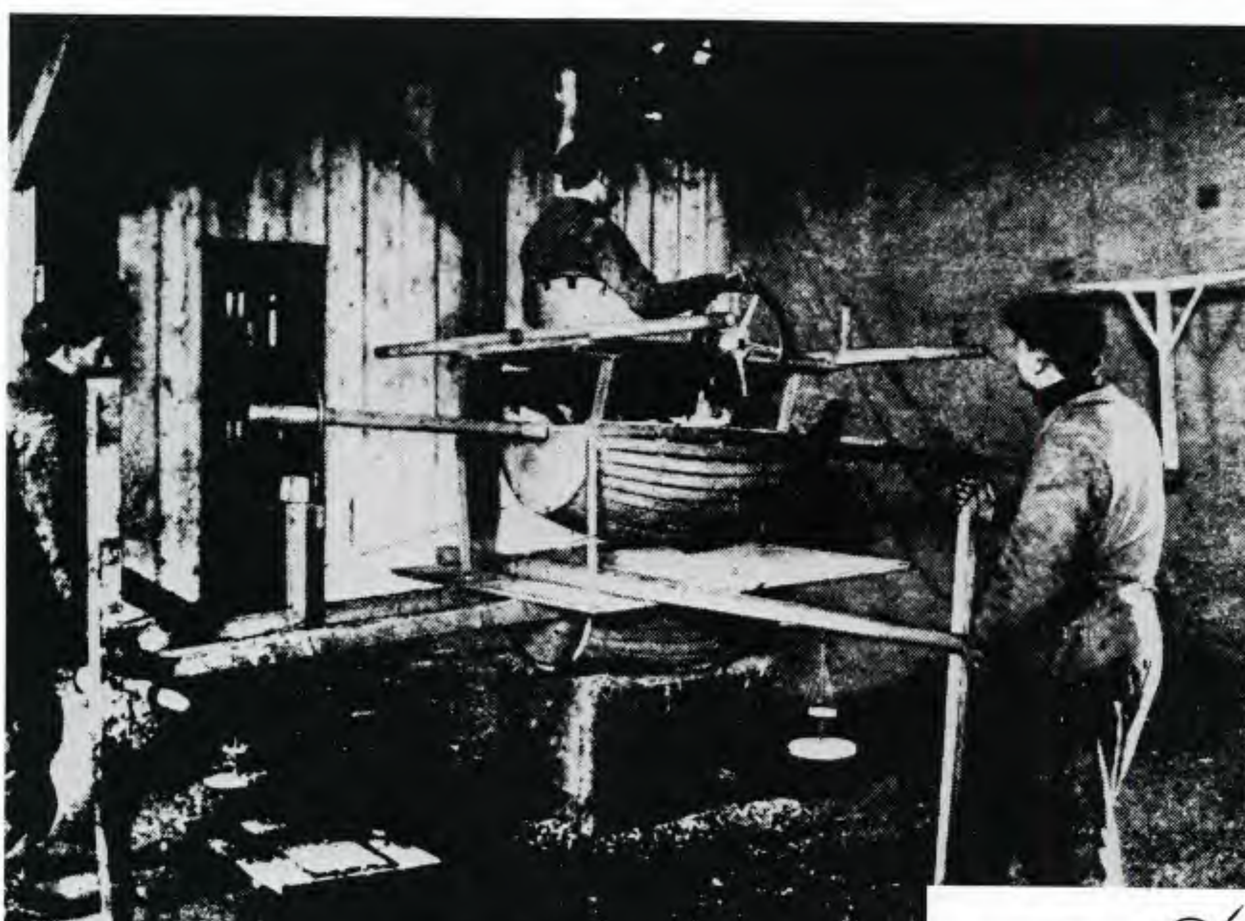

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Figure 21.

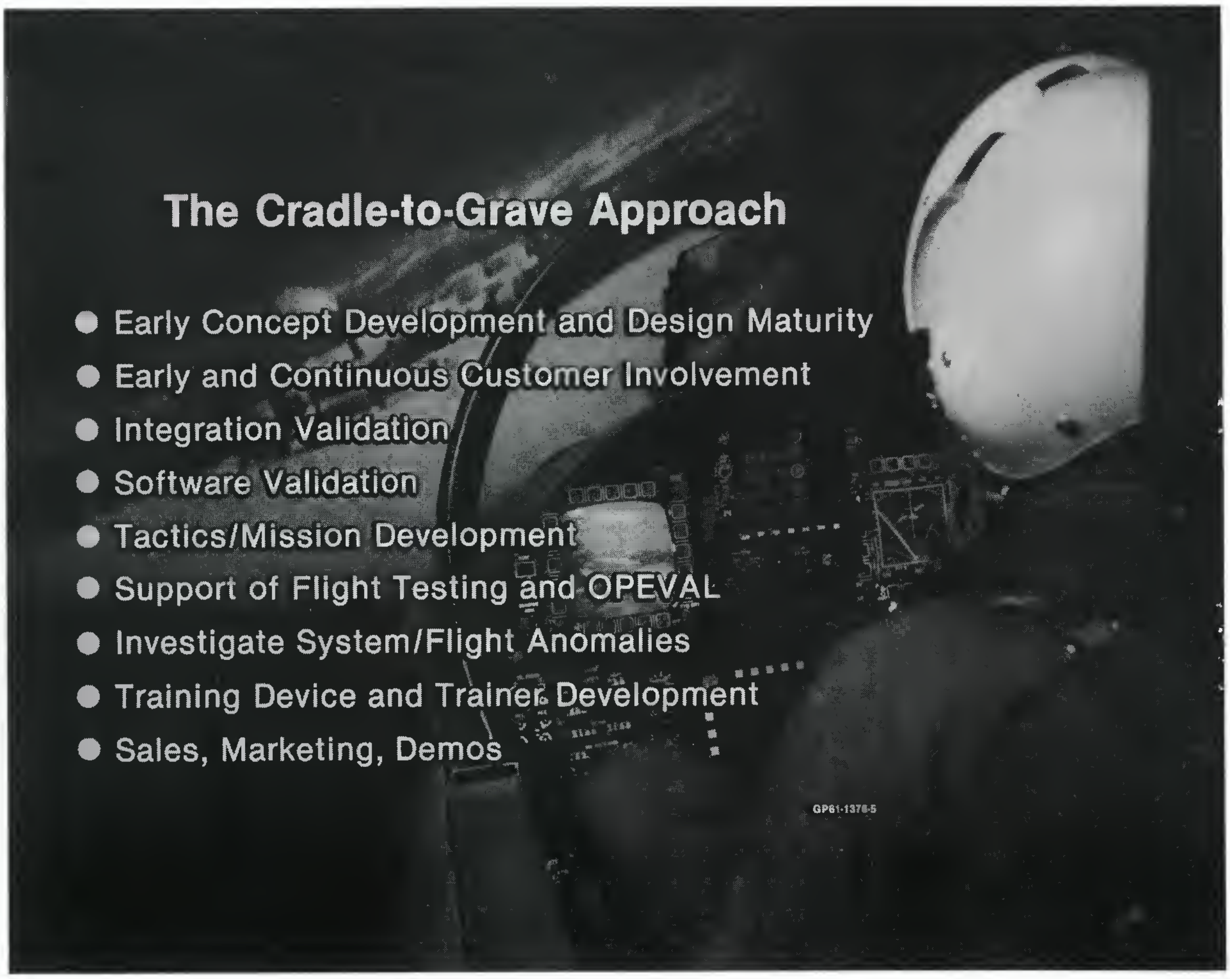

Figure 22.

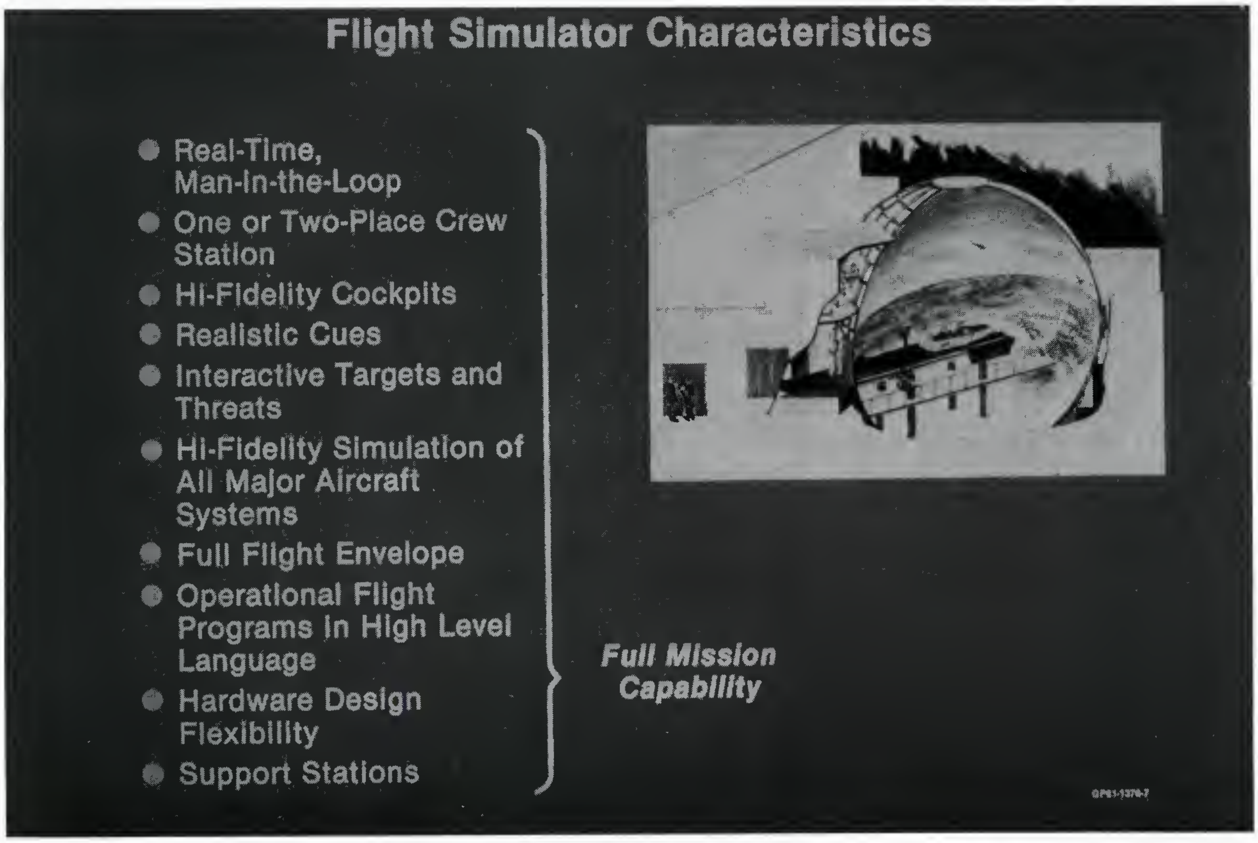

Figure 23.

Figure 24.

Simulation Support During Design/Development Phase

- Build Hi-Fidelity Simulated Cockpit
- Provide Hi-Fidelity Software Model
- Full Flight Envelope
- Full Mission Capability
- Customer Evaluation

Provides Data for Aircraft Implementation

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Figure 25.

Figure 26.

Simulation Support During Integration/Validation Phase

- Cockpit Built With Production Hardware
  - Controls and Displays
  - Mission Computer(s)
  - Flight Control Computer(s)
  - Others
- Flight Control Bench
- Full Envelope, Full Mission Capability
- Limited Field-of-View Visuals, Dome Compatible
- Validate Aircraft Software
- Evaluate Patches
- Some Systems Development

Provides Avionics Systems Hardware and Software Validation; Pilot Training; Flight Test Support

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Figure 27.

Figure 28.

Figure 29.

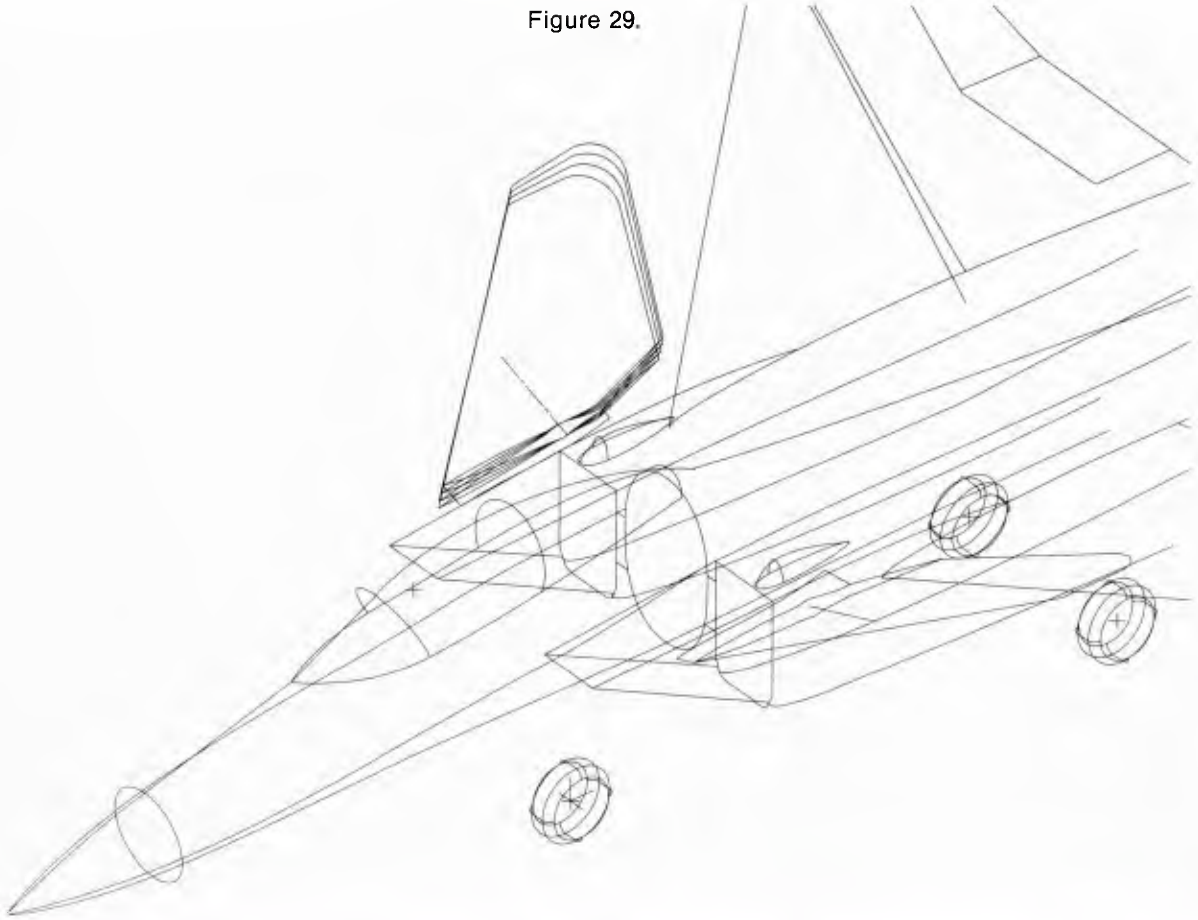

Figure 30.

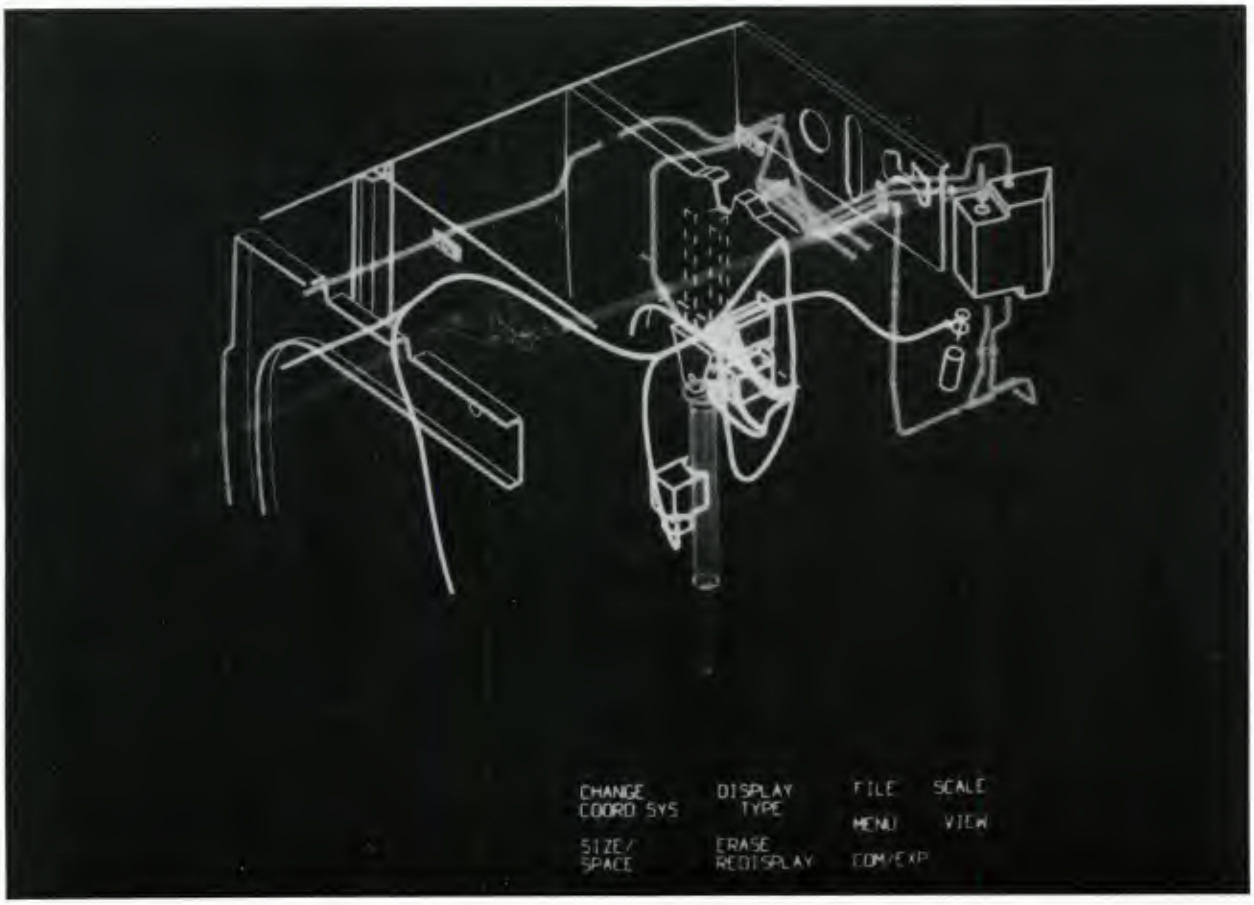

Figure 31.

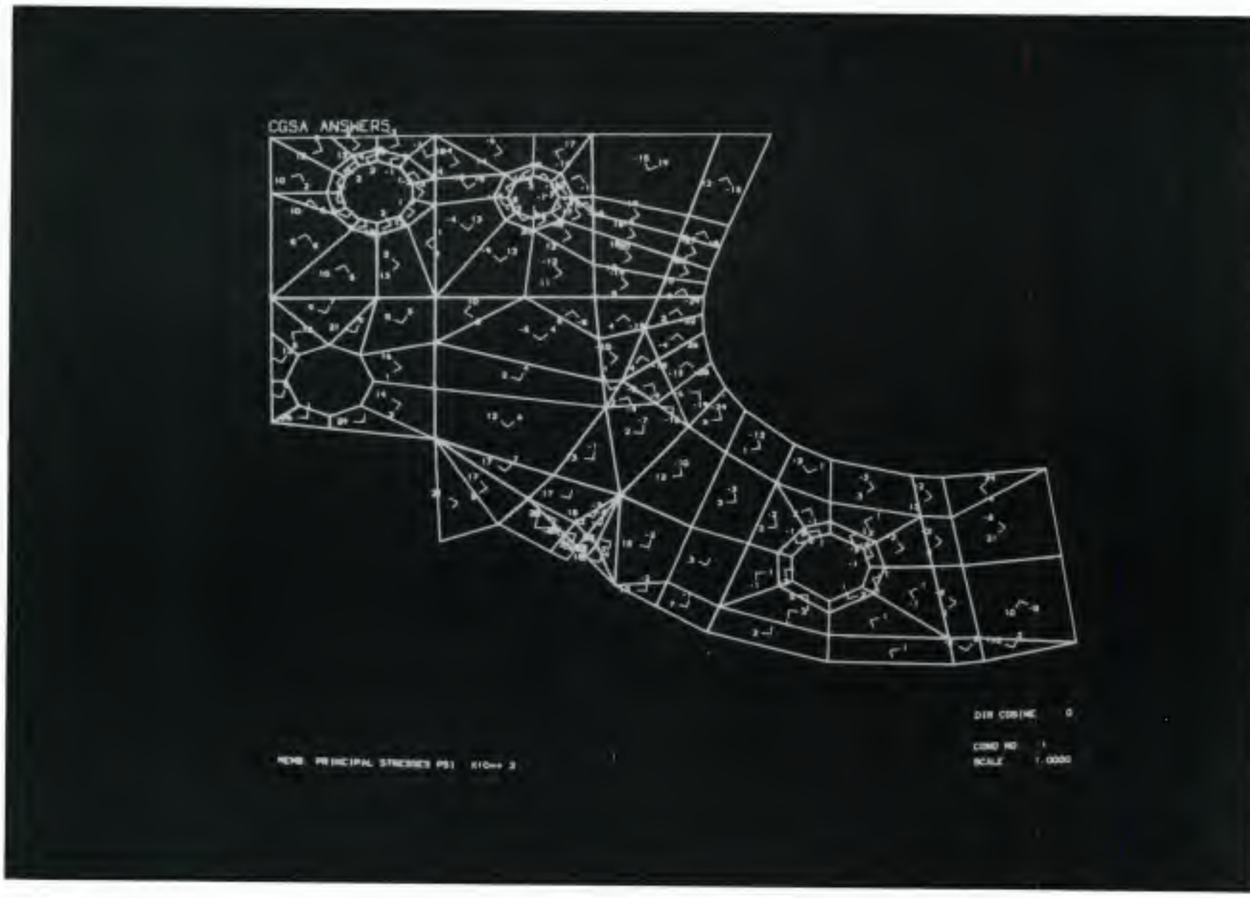

Figure 32.

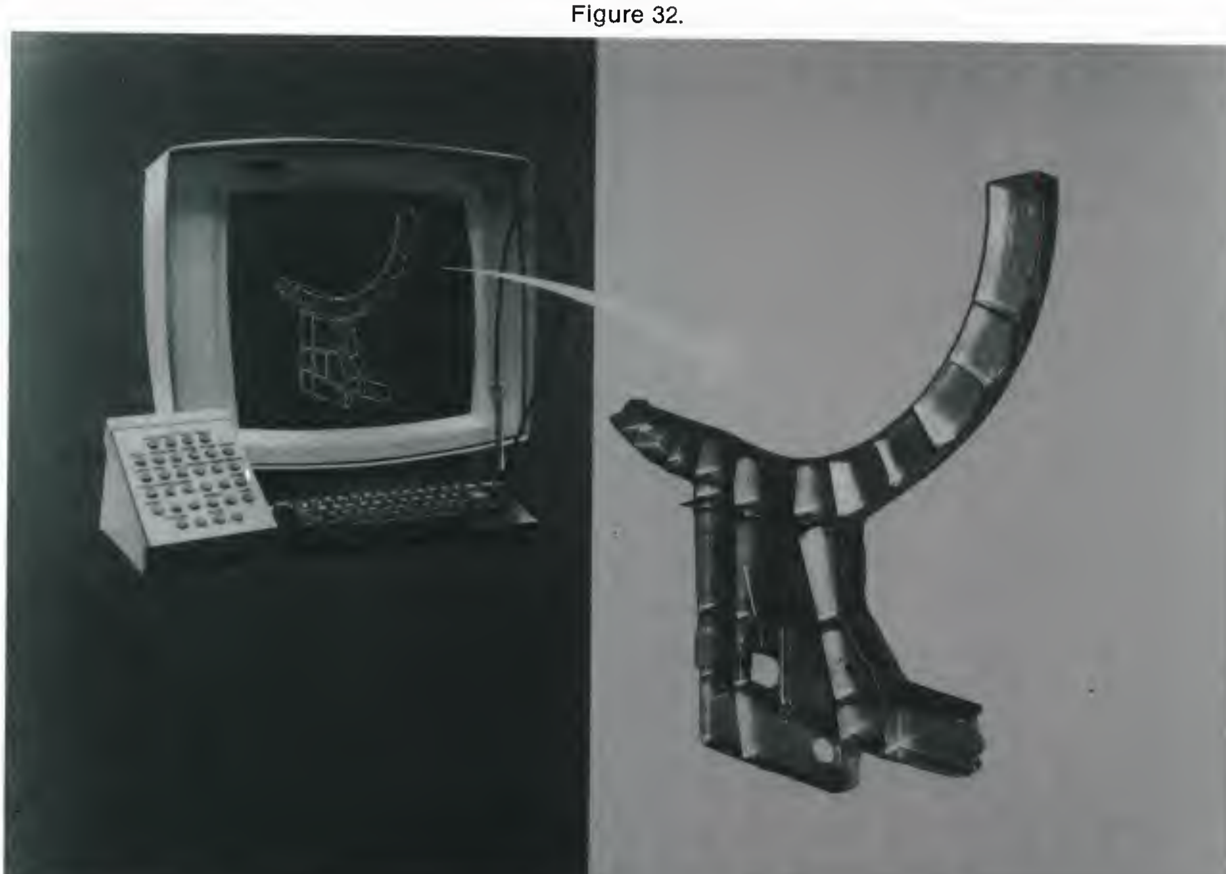

Figure 33

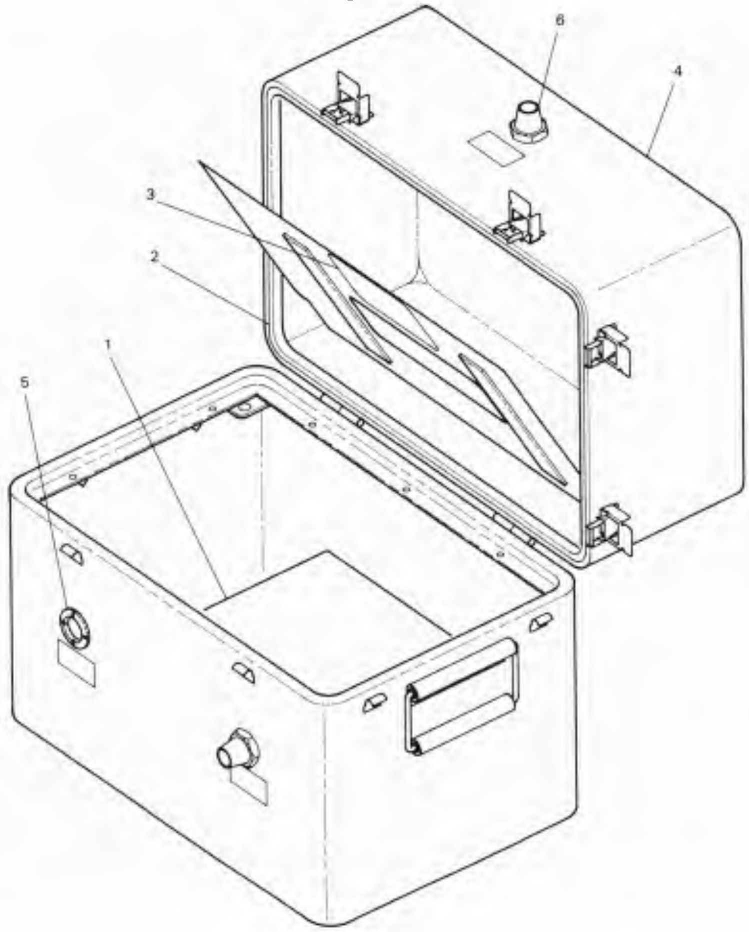

Figure 34.

V/STOL and STOVL Fighter Design

Clifford L Bore
British Aerospace
Kingston

INTRODUCTION

If an air-force has all its bases denied, its usefulness and value are zero: no bases means no use! This is where vertical landing fighters find their first essential advantage over all others, for they alone can choose where to land from an enormous range of sites. They would be the only aircraft operating. So in the first part of this lecture, we review a wide range of basing concepts, including dispersed land bases, small and very small ships, ski-jump and "Skyhook".

Next we turn to the design of STOVL fighter aircraft, starting from consideration of the engine and nozzles system, which is, of course, the heart of jet-powered STOVL fighters. This leads on to consideration of the nature of the aerodynamics of vertical landing, such as hot-gas ingestion, jet-induced suck-down and the "ground/jets fountain". Then the special features of air-intake design are considered, followed by the special considerations of lifting-surface design. Finally we consider the special features of "thrust vectoring in forward flight" (VIFF).

BASING TACTICS

Fixed Bases

Figure 1 shows a fixed base after an air raid. Nowadays, there would be fewer craters aimed more accurately, for techniques of runway denial are developing rapidly. Fixed bases are pre-targeted with runway and shelter destruction weapons, while long-term chemical and anti-personnel weapons will inhibit repair operations. Thus fixed bases will become more and more unhealthy and ineffective.

Dispersed Land Bases

Figure 2 shows a conventional dispersed base for Harrier aircraft. We can see this one because we knew where to look, but even with infra-red techniques it is very difficult to identify such bases,- and camouflage techniques are advancing. Furthermore, there should be a large number of potential bases available, with only a few occupied at any time. Thus dispersed bases are very difficult to identify, and even more difficult to put out of action as a working ensemble. The problems of logistics supply have been solved, of course. So the vital factor of base availability will be much higher (perhaps infinitely higher) than for targeted bases.

After deciding on dispersal for survivability, the next question is where should they be. If we can make them largely undetectable, they may be sited much closer to the target areas than fixed bases could ever dare. This has four important advantages:-

* Much shorter base-to-target distance allows smaller aircraft; and smaller aircraft are:-
    * easier to operate forward,
    * quicker to reload (less fuel ..)
    * less visible to the enemy, so less vulnerable,
    * cheaper, so can be more numerous.
* Quicker response to any order for attack.
* Less time and distance in transit to targets means less probability of interception.
* Forward bases allow earlier interception of enemy intruders.

The magnitude of such advantages depends on the eventual scene of operations (and who knows what that may be?). In the rugged territory of Brunei (for example) there were so few potential fixed bases that a typical fixed base-target distance would be over 300 miles, whereas forward bases may be at about 50 miles. Probably the distances would be similar for a terrain with a great deal of water and soft ground everywhere. Very important cases have arisen where the airforce has no land bases at all, so offshore platforms become the only possible bases. Great Britain could be covered using aircraft with a radius of action of 100 miles, and Europe requires about 300 miles radius. We will examine a range of offshore options shortly.

Versatility and flexibility have to be the main aims of any defence system, for otherwise the enemy only has to find a single weak link in our chain and cut that. Thus a system with multiple responses is essentially strong, while a system that relies on a single link (such as a 2,000 foot runway) is essentially weak. This lecture is, of course, too short to do more than sketch the outline of the many responses possible with a vectored-thrust vertical landing airforce. For more extensive reviews, see references 1 to 4.

Mobile Land Bases

The advantages of having bases that are unknown to the enemy can be carried further by providing truly mobile bases, that require no take-off strip at all. This can be done by employing mobile ski-jump vehicles (figure 3) which enable high-load takeoffs. Alternatively, Skyhook could be adapted readily to dispersed land bases (figure 4). Figure 5 shows a base for 6 Harriers and a Skyhook, in comparison with an actual fixed base.

Water Bases

Figure 6 compares the sizes of conventional flat-top aircraft super-carrier and the various types of "Harrier Carriers" that are coming into use in various navies. Broadly, one super-carrier has about the same mass as five of the RN command cruisers, or 12 of the projected Vosper Thorneycroft Harrier Carriers. The smaller ships have the important advantage that they can be literally in 5 (or 12) different places at once, and thus make a much more difficult target to disable. Further, they can cover a much wider area of sea or land than a single carrier. Figure 7 shows the smallest ship used so far for a vertical landing: the 2,300t merchant ship "Alraigo". The smallest conventional platform measured 55 feet by 85 feet (16m X 26m), and that was used when the ship was at anchor.

An important feature of the specially designed ships is their use of the "Ski-Jump" take-off ramp (figure 8). With Ski-Jump, a vectored-thrust aircraft uses a lot of free-air space as part of the take-off run, in which the aircraft completes its acceleration to fully wing-borne speed (figure 9). Because most of the take-off run is in the air, the weight of the take-off platform is very much less than that for a flat deck allowing similar payload. In fact, an aircraft with Harrier-like performance can take off with 10,000 pounds of load (that is an extra 2,500 pounds or 1,200kg load) from such a ramp, from a deck length only 1/4 to 1/3 of the corresponding flat-deck run.

It has been estimated that 30% to 40% of all ship-based aircraft losses would be saved by adopting ski-jumps. Pilots much prefer taking-off from ski-jumps, because their trajectories are never steeply towards the sea, as in flat-deck operations, and this is better for their nerves! The tactical and engineering considerations for V/STOL operations from ships are discussed in some detail in references 2-10.

Saving aircraft crashes and pilots' heart strain at take-off are only two of the many advantages that stem from STOVL aircraft operations, as pioneering test pilot John Farley notes with enthusiasm in reference 8. He concluded: "It is better to stop, then land; than to land, then stop". Figure 10 (from ref.11) illustrates the landing accidents aspect. The curves shown can be fitted by power laws: thus landing accidents on US carriers are proportional to the landing speed to the power of 2.5, while the land base accidents (N.B. on undamaged runways, with no enemy action) were proportional to speed to the power 2.22. Taking Kohlman's data points for Jets and VSTOL landings, the latter speed would reduce landing accidents by 86%. This is no idle theory, for the V/STOL Harriers have made a million landings, they have flown from more ships of more navies than any other fixed wing aircraft in history, and have made over 20,000 sorties from ships.

We have seen that the ability to land vertically brings in many advantages, such as very low attrition from landing and take-off accidents, and particularly low vulnerability to annihilation of bases. There is also safety in numbers, as well as safety from being undetected by the enemy. We will see also that there may be positive advantages to increasing the numbers of mobile bases, at sea. If one were to cling to the old convention of very few large capital ships, these become prime targets, such that defence of these targets becomes a main preoccupation, that may interfere with the original aim of protecting a wide area for safe passage. Under the old conventions, aircraft would be put up into continuous standing patrols, which entails aircraft of long endurance, flying for long periods of time, yet endowed with high dash speed in order to dash across the patrol orbit to intercept an intruder. So we would need many large high-speed aircraft to protect our prime liability. Let us examine another way of breaking away from the maritime version of the Maginot Line Mentality.

Skyhook

Suppose that we had 12 or more small ships, of around 5,000 tons each (figure 11) replacing one primary ship. Why not go smaller? The limiting factor is ship motion during take-off and landing. If we can get around that problem, we can operate in rough weather. The design studies that have been made over recent years are based on "Seastate 6", which is exceeded only 1% of the time worldwide, and only 2% of the time in the north Atlantic. Figure 12 shows a space-stabilised crane mechanism on a 4,000 ton ship. The technology is well-established, and it is easy to hover a Harrier within a 3m cube of space, in any weather. The grab of the Skyhook will steer itself to a device on top of the aircraft, which can then be lifted on board (if necessary) for replenishment. Fuel can be replenished through the Skyhook. An aircraft at the ready can be lifted overboard, engine started and on-route towards its target within 2 minutes. This affords the opportunity to mount a "sitting patrol", from numerous small ships protecting seaways or indeed landways over a very wide area.

The horseshoe arcs of figure 13 are based on 2 minutes reaction time and targets flying at M=1.3. Area coverage (excluding missile range) is shown in figure 14. A concept which has been studied in considerable depth is the Vosper-Thorneycroft Ski-Jump Escort Carrier (fig.11) which displaces 5,300 tons, carrying 5 Sea Harriers and 1 helicopter.

Basing Tactics: Conclusions

This brief review of basing tactics should be enough to show that vertical landing capability affords enormous versatility and flexibility of response, together with enormous reductions in base vulnerability relative to conventional take-off aircraft. In effect, by "Day 2" of any battle in a sophisticated scenario, the only aircraft remaining operational will be vertical landers. Furthermore, even if we were to imagine conventional aircraft that could survive the base denial attacks of the future, the CTOL aircraft would suffer substantial penalties such as considerably greater range and payload requirements, and also substantial extra fuel-reserve requirements for diversions or "going round again" at landing. As we go on to consider the internal design features of STOVL (Short Take-Off, Vertical Landing) aircraft, we will see that CTOL aircraft suffer various other penalties by comparison, such as absence of thrust-vectoring in flight. It is hoped that enough has been sketched here to show how operational basing concepts have powerful leverage upon the qualities and performance requirements for STOVL fighters.

SPECIAL DESIGN CONSIDERATIONS

As this course is concerned with high performance fighters, this concentrates our attention on jet-propelled aircraft with high thrust/weight ratio. Now current high-performance fighters need thrust/weight around unity for manoeuvrability and performance, so the basic propulsive thrust would be enough to land vertically, if it were vectored vertically. This consideration led, of course, to our datum configuration.

Engine and Reaction Control Choices

It is one thing to sustain the weight of an aircraft on its thrust, but it is also necessary to control the aircraft during low-speed flight at landing and take-off. In order to provide the necessary control moments, we may choose either to duct a relatively small fraction of the engine mass flow to the extremities of the aircraft for reaction controls (as in the Harrier family of aircraft) or, at the other end of the spectrum, use a relatively large fraction of the total engine mass flow at a fairly small moment arm. Figure 15 shows the basic dilemma. If the thrust were to be provided from compressed air or exhaust flow alone, the necessary ducts have to to be large if the moment arms are chosen to be small. Now large ducts need fuselage to surround them, at some cost in weight, so there is an obvious incentive to seek augmentation of the thrust obtainable from each unit of mass flow ducted. This line of argument leads to various possible aircraft layouts, which are being studied in some depth.

Vectored-Thrust

Since 99% of the world's operational experience in jet V/STOL is invested in the Harrier family,this is the natural choice of a datum, from which all the other layouts may be assessed. Figure 16 shows the vectored-thrust engine which powers the Harrier family. Almost all the gross thrust of the engine can be vectored from pointing directly forwards, to some 10 degrees past the vertical. For control, a fraction of the high-pressure compressor air is ducted to the extremities of the aircraft (figure 17) where it is controlled by simple shutters moving across the exit nozzles. The ducts are circular in section, so can be made of very thin metal, without great weight.

Vectored-Thrust + PCB

If we want supersonic performance, the aircraft will be longer and thinner and have heavier air intakes, and this roughly doubles the weight of the aircraft. So we need more thrust at landing and also more thrust per unit of frontal area during high-speed flight. It so happens that Plenum Chamber Burning (PCB) can provide both changes (figure 18). The air entering the plenum chamber from the low pressure compressor ("fan") before delivery to the front nozzles is not very hot and it has not had any oxygen burnt up. Since the thrust of a given nozzle flow varies with the square root of the temperature, by burning fuel in this chamber it is possible to double the front-nozzle gross thrust, or to increase the overall thrust by roughly 50%. PCB engines had been run successfully for 300 hours by 1965, when the supersonic P1154 fighter was cancelled (figure 19). That cancellation put supersonic V/STOL in the UK "on the back burner" for a very long time, but the work resumed since then supports the viability of that concept.

The first difficulty from this concept stems from the fact that while PCB increases the thrust of the propulsion engine by a large amount, fundamentally the quantity of air that one may bleed from the high-pressure compressor is not increased (though the engine design would be bent in the right direction). This means that for control, we want more thrust per unit of bleed flow. So the augmented reaction controls research of the early 1960's was resumed some years ago, and work has progressed on more active control systems.

The other problem is obvious: with very hot front jets, clearly there is much more risk of hot gas entering the air intakes during landing, and thus reducing the engine thrust, or even causing the engine to surge and stop. Because there are so many conditions to cover, and there have been difficulties in relating full-scale significance to model-scale test results, research into this problem is not yet complete. We will return to this topic later.

Vectored-Thrust + Lift Engine

In the period 1965-75, the concept of adding small lift engines (with very high thrust/weight) was popular, and several types were flown with some success: notably the VJ 101C, the VAK 191B, the Mirage III V. The only representative of this type to go into series production was the Russian YAK 36 "Forger", which will be discussed in more detail shortly.

The arguments in favour seemed plausible at the time (to some people). Firstly, the specialised lift engines had a considerably higher thrust/weight than propulsion engines. Secondly (it was argued) the propulsion engine could be sized for cruise and on-route performance (rather than for the full-load vertical take-off which was then fashionable) and so could have smaller specific fuel consumption during most of its mission.

Williams (reference 12) gives a perceptive assessment of this concept, along with the other European types. Firstly, the installation factor for the weight of lift engines came out to about 2, compared with about 1.5 for propulsion engines, so the weight advantage was much reduced. Secondly, it was later realised that it was unrealistic and unnecessary to specify full-load VTO, for a considerable boost in payload is possible from a very short take-off run. Thirdly, the on-route performance requirements for fighters have been going up so much that they now need a thrust/weight over unity in any case. In addition, special lift engines were expensive, and their thrust could not be vectored much during take-off or landing transitions, and they conferred no benefits at all in high-speed manoeuvring.

Figure 20 (from reference 7) shows some of the crucial considerations which arise from this concept, by comparing the YAK 36 Forger with the Harrier. The table of performance data and capabilities shows that because the propulsion engine is a straight turbojet, its cruise SFC is almost double that of the Harrier. In hover and transition, the rate of fuel consumption is around double that of Harrier, and because the lift engines cannot be vectored much the transitions take 3 times as long. Thus fuel consumed in take-off must be about 6 times as much. This machine cannot do STO or ski-jump, and any capability for thrust vectoring manoeuvres at high speeds must be weak. Furthermore, the strong infra-red signature from the propulsion engines is barely shielded by the aircraft.

Next look at the diagram in figure 20 llustrating the Forger's control problem in VTOL. With two lift engines forward taking half the weight, this ensures that if any one engine out of 3 fails, the aircraft crashes. This would more than treble the loss rate from engine failures. Again, one may question what is the thrust/weight for the propulsion engine: if it were over unity, the lift engines would be unnecessary. Thus the manoeuvrability and agility at high speeds must be inferior.

At this stage it is worth remarking that examinations of this sort can illuminate the relative merits of different concepts remarkably clearly.

Remote Augmented Lift System (RALS)

Figure 21 shows the basic features of RALS. The primary difference from the VT concept stems from providing a duct from the outlet of the fan plenum chamber forward to a vertical outlet, for use at landing and take-off (VTOL). Reheat can be applied to this efflux, as it is in the PCB concept. When operating in normal propulsive mode, the forward ducting from the fan plenum chamber is closed, and the flow proceeds aft to a conventional propulsive nozzle, where again it can be reheated. Thus the thrust can be boosted to PCB levels for both the VTOL and propulsive modes. The main advantage over PCB is that the fan lift thrust during VTOL can be considerably further forward relative to the main engine, so the engine can be positioned further aft in relation to the centre of gravity. One disadvantage is that a diverter valve has to be provided, at a cost in weight, complexity and money. In some applications it may be possible to vector the front augmented lift nozzle to some degree, but at some stage there has to be a switch-over stage where the plenum chamber flow is being switched from VTOL mode to propulsive mode. This restricts the short take-off, ski-jump and thrust-vectoring-in-flight (VIFF) capabilities. As we will see later, the RALS ducting occupies considerable volume, and this has to be surrounded by fuselage at a weight and cost penalty relative to PCB. Another important consideration is that the hot efflux from the front RALS nozzle during VTOL emerges further forward in relation to the air intakes, and this may worsen the hot gas ingestion problem. Thus RALS could be regarded as a PCB system modified so that the main engine can be placed further aft, with penalties of weight, cost and capability.

Ejector Augmented Lift

Figure 22 shows one version of an ejector-augmented lift system, which is very similar to the RALS except that the augmentation of the thrust at the forward lift nozzle is now to be accomplished by ejector aerodynamics instead of reheat. There is an immediate advantage over RALS in that the front-nozzle efflux will be cool, so the hot-gas ingestion problem is eased. If conventional ejector mixing is to be used for the front-nozzle thrust boost, the maximum augmentation will be limited, and the volume of the ejector unit will be larger than that of RALS. (Greater thrust augmentation could be achieved by using air-driven fans, at a cost in mechanical complexity and volume.) Thus this system seems better than RALS from a hot-gas re-ingestion (HGR) point of view, but otherwise is similar to RALS. Unfortunately, HGR is not as simple as that, for the front-nozzle flow has low dynamic pressure, so that the hot rear-nozzle flows may penetrate forward and still cause re-ingestion.

Figure 23 shows a version which takes ejector lift augmentation further by taking all the engine effluxes into ejectors for the VTOL mode of operation. Since the rear-nozzle effluxes (in the VTOL mode) are diluted with cool air, the entire hot-gas ingestion problem is eased, and any problems associated with overheating or erosion of the ground will be eased or eliminated. Against that, thrust vectoring will be restricted to perhaps 45 degrees, so that short take-offs, ski-jumps and VIFF may be restricted. Another point is that major holes in wing or fuselage for ejector units impose weight penalties and may interfere with store carriage requirements.

Tandem Fan

Figure 24 (from reference 16) shows the layout of a tandem-fan engine. In the propulsive ("series") mode, the engine can be regarded as a mixed-flow bypass engine, with part of the fan flow supercharging the high-pressure compressor and part bypassing, to mix with the turbine efflux before the propulsion nozzle. In this mode, reheat may be applied to the whole of the mixed flow, so a high level of thrust could be achieved.

For the VTOL ("parallel") mode, a shutter closes across the plenum behind the first-stage fan, and outlets from the plenum open, so that the flow from the first-stage fan is ducted out through the front lift nozzle. The second-stage fan now has to draw its air from the rear part of the plenum, so inlets have to be opened into that from VTOL air intakes. As before, the second-stage fan supercharges the high-pressure compressor and also feeds the bypass flow. In this mode, the rear nozzle is vectored to exhaust the mixed flow lift-wise.

In a hybrid version of the tandem fan, (figure 25) the outlet flow from the first-stage fan is ducted to a vectored-thrust nozzle. This would improve the operational usefulness for very little penalty.

With this system, the engine can be designed for two different modes: a high-performance propulsion mode, and a reasonably matched VSTOL mode. The penalties relative to "Advanced Vectored Thrust" (AVT) are increased complexity and volume.

Comparative Assessment of Engine Concepts

Figure 26 shows the various engine concepts to the same scale. Much of the ducting will be hot (and heavy) and this makes much of the surrounding volume unsuitable for stowage of equipment. All of the engine system has to be surrounded by fuselage or wing structure, at a penalty in weight. Extra surface areas outside the fuselage, or inside air ducting, incur extra skin friction losses. Evidently any choice of "Best Buy" will have to judge the value of the potential advantages against these weight and cost penalties.

Some concepts claim advantages in terms of HGR, so it is instructive to compare the exhaust gas temperatures, as shown in figure 27 (from reference 15). The first pair of columns relates to the subsonic Pegasus engine, which powers the Harrier with no significant trouble. The AVT (i.e. vectored-thrust + PCB) has hotter exhausts, which entail substantial research. The RALS (and tilt nacelle) may be hotter still. The tandem fan and the ejector augmented lift systems offer less problem so far as HGR is concerned.

Thrust available in the propulsive mode influences agility, and this is compared in figure 28 (from reference 15). It can be seen that RALS offers more thrust, while the ejector lift concept and the tandem fan offer slightly more thrust than AVT. Finally, the addition of special lift engines to a VT engine leads to inferior thrust, as we saw earlier.

It is not possible to go much further with comparisons at this level of simplicity, for there are so many interacting considerations. This is why the various more promising concepts are under detailed engineering study. Even at the end of those studies, the answers will not all be plain, for some of the problems will not have been researched to a definitive stage. Even if several types were built and flown (as happened many times in the past) some types may not reveal their fatal flaws until a lot of experience has been obtained the hard way. It is always worthwhile to try to learn the lessons of previous experience, and the main one is that complexity is costly and may be dangerous: more complexity may mean more ways to crash. For more thorough background, it is worthwhile reading more extensive reviews, such as reference 13 (embracing references 14 - 16 and more) together with reference 12. If history is any guide, there will be 20 concepts to test for each one that works well enough!

AERODYNAMICS OF VSTOL FIGHTERS

Having considered the special aspects of basing tactics, and the "heart" of any VSTOL fighter (the engine/control system) we have one major field of special aspects remaining: aerodynamics. Most of the special considerations arise from the fact that VSTOL aircraft have to operate satisfactorily at very low flight speeds, with high-thrust jets blowing perpendicular to the aircraft, as well as in usual flight conditions. This field is extensive, and it has been reviewed in some depth in reference 13. That report details the content of a 5-day lecture course, but we have half an hour left, so there is only time to outline the main principles involved.

Let us start from the main aim of the exercise: getting a substantial payload off the ground and on-route, or landing an aircraft with some of its payload. The payload is dominated by the difference between the useful net lift force and the empty weight of the aircraft.

ENGINE/CONTROL SYSTEM LOSSES

Suppose that we have an engine which would deliver a given thrust if tested on a test-bed with highly efficient air intakes and nozzles. When we fit this with non-ideal air intakes and nozzles, a few percent of the thrust will be lost. If we now bleed off a substantial mass flux of compressed air from the high-pressure compressor, the temperature limiter will cut back the fuel supply and thus cut the thrust. These may be regarded as losses associated with the engine/control system. We will consider how to design for low losses, starting with the air intake, and proceeding via engine sensitivities to the exhaust nozzles.

Air Intake

The best known source of thrust loss from the air intake stems from loss of total-pressure recovery in the air intake flow. For brevity the term "total-pressure recovery" will be replaced here by "intake efficiency". Now each 1% loss of intake efficiency will cause a loss of 1% to 2% of engine thrust, depending on the engine design and also on where the area of total-pressure loss is situated on the entry to the compressor. For example, on a bypass engine the engine is likely to lose more thrust when the total-pressure loss region is within the inner annulus of flow, which leads on towards the high-pressure compressor. To illustrate: if an air intake were to present a 2% efficiency loss in the inner annulus of a sensitive bypass engine, up to 4% loss of thrust may ensue. If the payload represents 40% of engine thrust, then that 2% loss of intake efficiency would lose 10% of payload. So we take a lot of care to reduce intake losses.

Now the efficiency of a round lipped air intake depends on the ratio of the "bell-mouth" area to throat area, as shown in figure 29 (reference 17,18). At zero flight speed, the direction of each part of the bell-mouth area is determined by the direction of its intake throat, so auxiliary intakes facing sideways are just as effective; but note that every inlet must be rounded well. Intake losses can be regarded as stemming from practical failure to realise the ideal bell-mouth force, and this is emphasised in reference 19. This concept enables one to find the air intake efficiency by measuring the thrust on the bell-mouth directly (and also helps with ejector augmentor theory) but it gets less useful with auxiliary intakes.

An engine may also lose thrust if its compressor is presented with flow which has an unduly large variation of local Mach number across it, from severe curvature of the duct at that station. This is called "static pressure distortion". This because the blades have to work at excessive lift coefficients, or excessive Mach numbers, in some positions.

Similarly, total-pressure distortion (as measured by a "distortion coefficient" over an angular sector: DC 60) may lead to some loss of thrust; but more seriously, if too many blades stall, the compressor will surge and stop the engine.

Hot Gas Re-ingestion

If a substantial amount of hot air is ingested uniformly into the air intake, the mass flow for given compressor-face Mach number is reduced, and with it the thrust. The situation would be worse if a substantial blob of hot air were ingested into part of the compressor face, for then the "temperature distortion" causes different parts of the compressor to face radically different local Mach numbers and lift coefficients, and this (like the other flow distortions) may stall enough of the compressor to surge it. The criterion for surge may be expressed for the worst sector affected, by a "temperature coefficient" over a particular angle of fan sector (theta). For example, for a particular engine it may be found that theta is about 120 degrees. Then it would be said that "TC 120" should not to be greater than some specified number.

The aerodynamics of Hot Gas Re-ingestion (HGR) is a substantial study in itself (see reviews in references 20,21). The basic problem with a multi-jet aircraft is that after the vertical jets meet the ground, the spreading sheets of efflux meet each other and "fountain" upwards with some vigour (see figure 30). When the aircraft is near the ground (say 10 feet, or 3m) these fountains of diluted jet efflux meet the underbelly of the aircraft and flow around it, and some of this flow may be ingested into the air intake. At the same time, this fountain flow provides a lift boost which is too useful to be spoilt without good reason, as we will see later.

It happens that on the Harrier, the cool front jets dominate and very little trouble arises, but if the front jets are to be hot, then we need to take a lot of care to ensure that very little of the hot fountain gets into the air intakes. A cross-dam under the fuselage aft of the air intake entry, combined with side strakes along the underbelly, increases the fountain lift by redirecting the fountain flow downwards again, so that only occasional blobs of warm air will be ingested. However, this is easier said than done, for we have to test models with hot jets extensively in order to design good underbelly devices and check that the HGR will be acceptable during all likely combinations of aircraft attitude, throttle setting and ambient wind. What is more, this sort of research will be needed for each new layout considered. Figure 31 shows the hot gas re-ingestion facility at Kingston, which allows the model aircraft to be moved in any trajectory, with different temperatures to front and rear nozzles, while sucking flow into the intakes. A fan simulates ambient wind with any velocity profile, from any direction.

Whenever one starts testing models which have many effective physical parameters, one meets the problem of finding which scaling rules to adopt in order to relate the model tests to the eventual full-scale aircraft. Classical dimensional analysis will not help a lot, because a comprehensive dimensional analysis will throw up a large set of dimensionless groups which must be held the same for model and full scale. We expect Reynolds number, Mach number, Grashof number and so on,- until eventually, for a complex situation, there will be only one possible model: the full-scale aircraft! In such circumstances, engineering analysis is more instructive, for it concentrates attention on the particular features which are thought to matter most.

In general, there are two transformations to be made when using scaling rules: first the choice of an appropriate group of parameters which should be the same for model and aircraft; then a rule for transforming the model-test measurements to their full-scale equivalents. It has to be noted that reference 22 shows comparisons between model and aircraft tests (VAK 191B) which agree quite well. At the time of writing, the writer has not yet been able to obtain copies of the VFW reports on the scaling rules used, so cannot describe their methods. It seems reasonable to suppose that they have some similarity to the rules used in the UK, which are still being modified in certain respects.

The basic principle is that blobs of warm air (detached occasionally from the sheet of efflux on the ground or from the jet fountain) should follow trajectories similar to the full-scale versions, and with scalable temperature rises. It is emphasised that these ingestible blobs (or bubbles) of air are to be "warm",- not hot, for if any blobs of undiluted hot-jet efflux were to get into the intakes, the engine would stop. Hot-jet concepts can be made to work only by designing so that only highly diluted efflux can ever get ingested. For similar trajectories, the ratio of warm-air bubble speed to efflux speed (across the ground) must be equal for model and aircraft. A recent analysis (reference 23) suggests that the similarity group should be of the form:-

$$\left(\frac{V_J}{V_B}\right)^2 \propto \frac{T_{TJ}}{gh}\left(\frac{r^{2/7}-1}{r^{2/7}}\right) \Big/ \left(\frac{T_B}{T_o}-1\right) \quad \text{where } r = \frac{p_{TJ}}{p_o}$$

Unfortunately that equation contains the temperature of the warm-air bubble, which is part of the unknown (a priori) results of the tests. In principle, a different configuration of jets and underbelly devices may lead to a different relation between bubble temperature and jet temperature. However, for any given class of configuration it should be possible to find the appropriate rule. For example, if entrainment were to follow the Ricou and Spalding rule (reference 24) the similarity group then becomes:-

$$\left(\frac{V_J}{V_o}\right)^2 \propto \frac{T_{TJ}}{gh}\left(\frac{r^{2/7}-1}{r^{3/7}}\right)\left(\frac{T_{TJ}}{T_o}\right)^{\frac{1}{2}} \Big/ \left(\frac{T_{TJ}}{T_o}-1\right)$$

We will not go deeply into the temperature scaling rules here. Suffice it to state that the temperature rise of any warm-air bubble will depend first upon the excess heat (enthalpy) injected into the space under the aircraft, and secondly the rate at which that heat gets diluted and convected to an ingestible location. The latter can be modified by the ingenuity of the engineer.

Reaction Control Bleed Effects

If the control moments for VSTOL were provided by compressed air bled from the fan, there need not be much loss of thrust, provided that the reaction control jets were arranged to be liftwise: only duct and nozzle losses would arise. However, low-pressure ducts are bulky, so high-pressure bleed is used on the Harrier family. In this context, concepts like RALS and ejector augmented lift can be considered as alternative ways of getting control moments without great lift penalty (but the weight penalties also must be considered).

Now consider a VT jet engine which provides high-pressure compressor bleed flow for reaction control purposes. This flow is not steady: brief pulses of flow may be all that is needed for roll or yaw control, though for pitch trim the moment may be more nearly continuous. The engine fuel controls will be set up so as to accommodate the continuous bleed, plus some margin for transient demands. Suppose that a substantial pulse of extra bleed flow is demanded suddenly: then less airflow passes through the combustion chamber and on to the turbine. Since the fuel flow is undiminished at this time, the temperature at the turbine entry increases. Soon the turbine blades heat up, and the turbine exit temperature, so the fuel control reacts by reducing the fuel flow and the thrust. A good control system allows the engine to develop a lot more thrust (say 30%) for a very short time, or a moderate increase of thrust for a moderate time, for we would rather have an overheated engine than a bent aircraft. Also we can provide water injection, which allows more thrust for a short time, especially for hot atmospheres. However, at the end of all these tricks, if we bleed much less time-averaged flow, the thrust can be increased. For this reason R&D seeks to minimise the amount of bleed flow, both by developing a sensitive active control system and by augmenting the thrust/mass-bleed at the reaction control units.

Nozzle and Bend Losses

The most obvious loss to avoid is splay of the effluxes in the VSTOL mode: simply the cosine component of the thrust vector, instead of the entire thrust. For small angles this matters little, and there can be good reasons for special bits of splay. Another significant source of loss is bends in the ducts (say 0.5% thrust for each right angle bend). To reduce these losses, Pegasus developments now use "droop and trail" nozzle layouts (figure 32).

Suckdown and Fountain Lift

Figure 33 shows typical graphs of suckdown force against height. This force can be regarded as a downward drag on the planform area of the aircraft, in the downdraught caused by the jet efflux columns and the effluxes spreading over the ground. The jet columns do not entrain very vigorously, so the suckdown force is only one or two percent of thrust at heights above 10m. As the jet effluxes spread vigorously across the ground, the mixing area and entrainment increases rapidly. With a single jet in the middle of the planform, the suckdown could increase to perhaps 30% of the thrust, at touchdown. However, if the designer is clever enough to arrange that there are 3 or 4 jets, well spread apart, a vigorous jet fountain arises, which can redirect the flow downwards and thus react a substantial increment of lift. For the configuration illustrated, the fountain lift starts at around 5m height, and limits the maximum suckdown to about 4% of thrust. At lower heights, a wide variety of fountain lift characteristics can be provided, by altering the array of dam, strakes, and the jets. If required, this can be arranged to provide a lift increment greater than the suckdown force, and give the effect of a "ground cushion" to land into. While this may be useful at landing and also during short take-offs, it will not help a vertical take-off through the worst point at 5m height.

We have now seen that the jet fountain can be very useful in offsetting the jet-induced suckdown force,- at the price of having to do a lot of research into minimising HGR.

Special Features of Lifting Surfaces

Wing design for vertical-landing aircraft is influenced more than one might think. Firstly, a vertical lander has the advantage over CTOL aircraft that it never needs to rely on the wing + flaps alone at landing, for it can always vector the thrust. Thus the wing may be smaller than for CTOL, which reduces the structure weight, as on the Harrier. Small area also helps reduce the suckdown force. If the nozzles are too close under the wing, local suctions may arise on the undersurface, as shown in figure 34 (reference 25).

Clearly low weight is a major asset for the wing, and this tempts the designer to increase the root thickness as much as possible. However, this must not be overdone, as illustrated in figure 35. If the root is too thick and too convex on the underside, supercritical flow may arise in subsonic flight,- leading to extensive shock waves and correspondingly high wave drag. Pylons and underwing stores would increase this wave drag. Local area rule, together with a "droop and trail"-nozzled engine, would help.

Tailplane design is influenced, for the jet effluxes passing close under a conventional tailplane induce large variation of downwash with incidence, so that a flat tailplane would produce relatively little pitching stability. On the Harrier there are substantial sidewashes near the tail, so these were used by adopting anhedral to produce stability. One must also avoid undue tail buffet.

Thrust Vectoring in Forward Flight (VIFF)

The first point to note here is that the forces acting on an air-intake and nozzle system are as sketched in figure 36. In this context, the stream force acting aft on the air intake is equal to the momentum drag, while the stream force vector acting on the nozzle is the gross thrust (i.e. the net thrust plus the momentum drag). Thus when we vector the thrust we soon find a fierce deceleration axially, plus an increment in normal force: both accelerations being of the order of 1g. Both accelerations occur before an adversary can see the intentions, (unlike fighters which have to alter incidence in order to accelerate). It so happens that while using VIFF the pitching stability of the aircraft is reduced, so a Harrier is able to pitch very tightly indeed, and quickly get onto the tail of any aircraft unwary enough to get behind in the first place, and shoot it down. This unique ability helps the Harrier to outfight all other fighters, as has been demonstrated either in actual combat or piloted simulators. Thus VIFF transforms a fighter with a very small wing into a truly formidable air combat fighter. The ability to deploy VIFF must be accounted an important asset available to V/STOL fighters. So any aircraft which is incapable in this respect suffers a relative penalty.

Concluding Remarks

The task of outlining the salient features of vertical landing fighters in a single lecture has been a formidable challenge, but it is hoped that this lecture has drawn attention to the extra basing versatility, the literally vital advantage of using bases that are not pretargeted by the enemy, and the asset of VIFF in air combat. On the technical side, the competing merits and demerits of various concepts have been discussed, and the special features of aerodynamics have been outlined. In all cases, references have been quoted which should enable those interested to dig deeper than time has allowed here.

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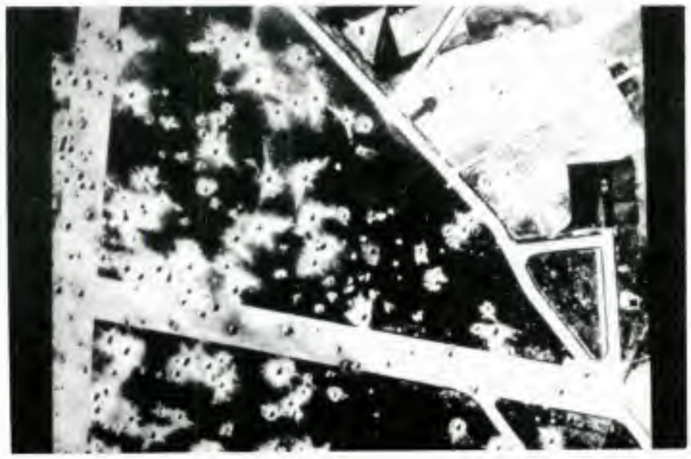
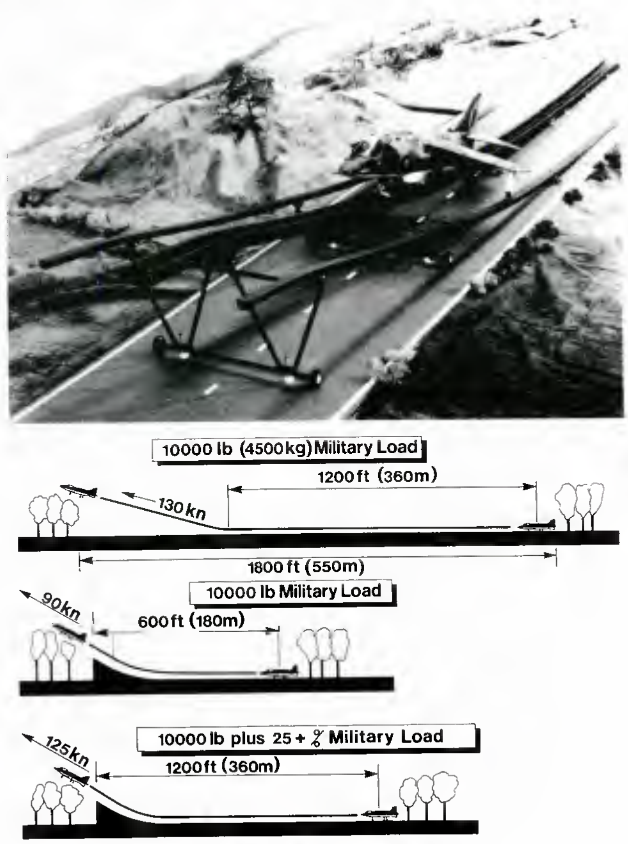


Fig. 1 Fixed Base after air raid (WW2)

Fig. 2 Dispersed Harrier base



Skeletal Ski-Jump. The Rail Ramp Proposed in 1979 for Off-Base Land Operation of Harrier

Fig. 3 Mobile Ski-Jump scheme

Fig. 4 Mobile land Skyhook

A. Typical NATO airfield

B. Mobile site with 6 aircraft

Vulnerability

Fig. 5 Bases comparison: (A) Fixed Base (B) Skyhook + 6 Harriers

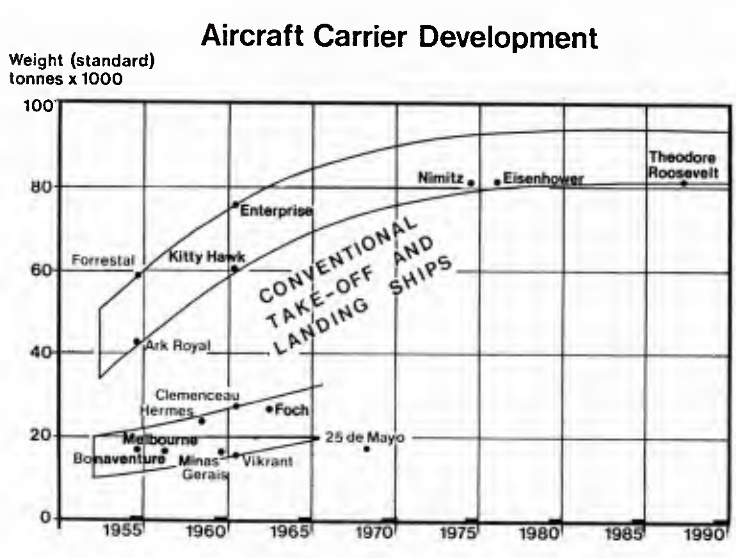
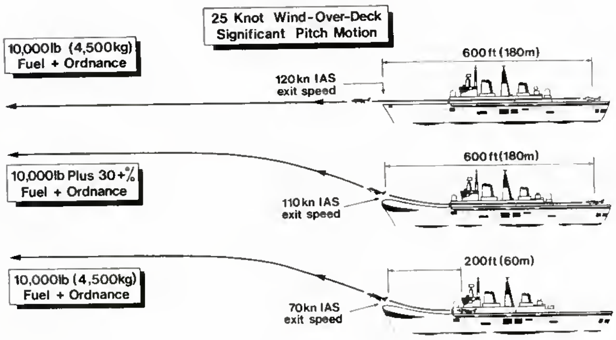


Fig. 6 Aircraft carrier sizes

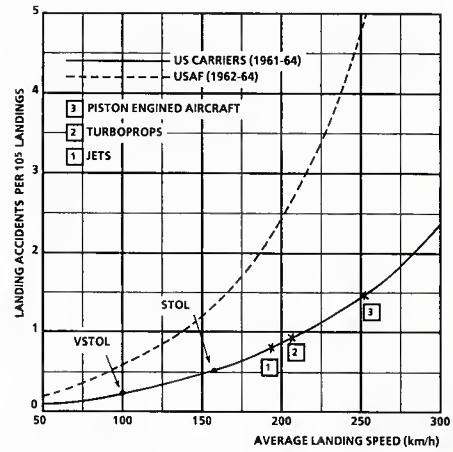
Fig. 7 Alraigo, 2,300t impromptu base !

Fig. 8 Ski-Jump



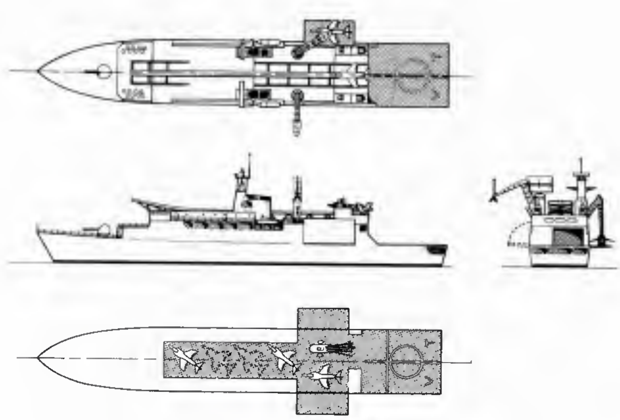
15 Deg. Ski-Jump. Shipborne Performance Gains

Fig. 9 The runway in the air, from Ski-Jump



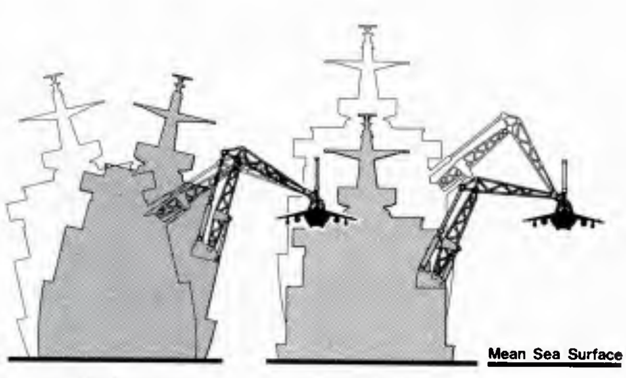
Speed vs. Risk in Landing

Fig. 10 Landing accident rates



Ski-Jump Escort Carrier

Fig. 11 The V.T. Harrier Carrier



Motion Capacity

Fig. 12 Ship motion capacity for Skyhook

Fig. 13 **Area coverage by interceptors from Skyhook**

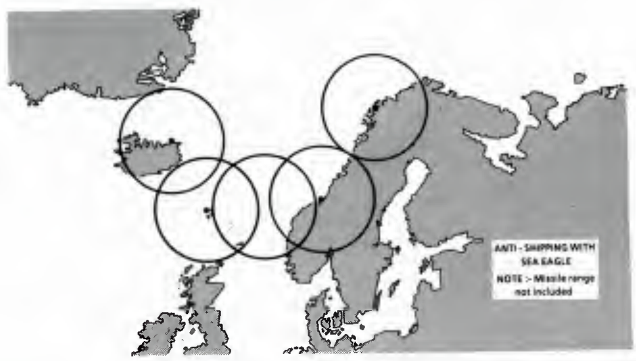


Fig. 14 **Area coverage by intruders from Skyhook**

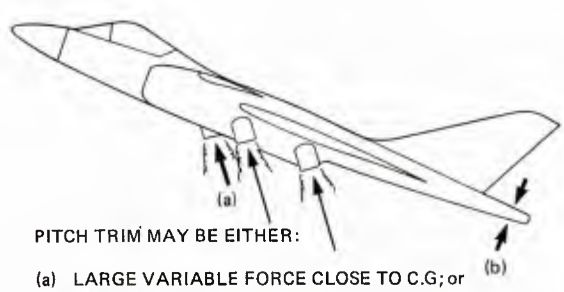


Fig. 15 **Control moment alternatives**

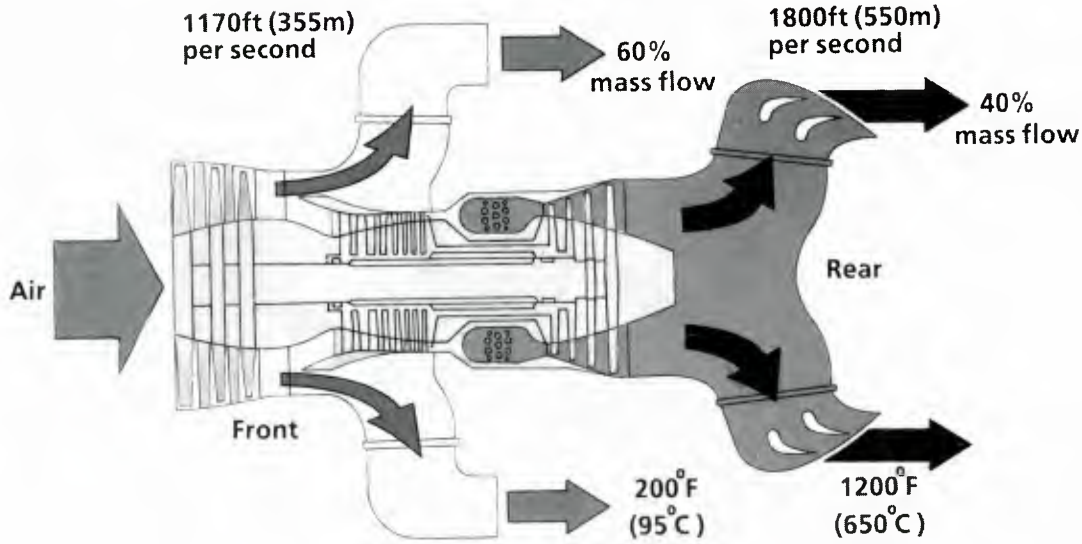


Fig. 16 **Pegasus Vectored-Thrust engine**

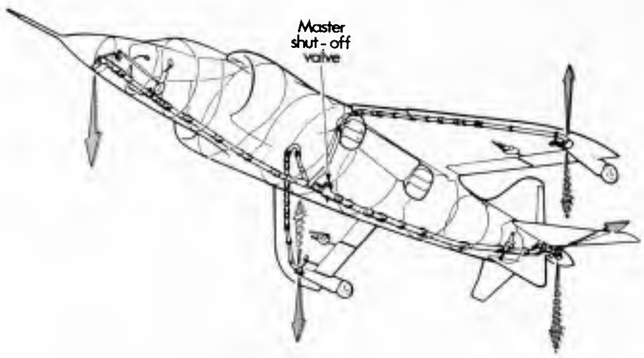


Fig. 17 Reaction control system for V.T. aircraft

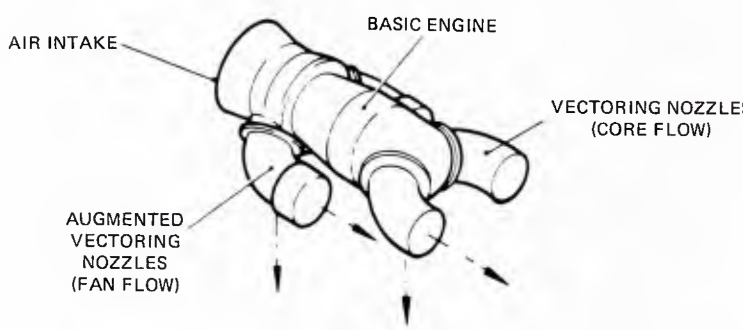


Fig. 18 Plenum Chamber Burning (PCB) engine

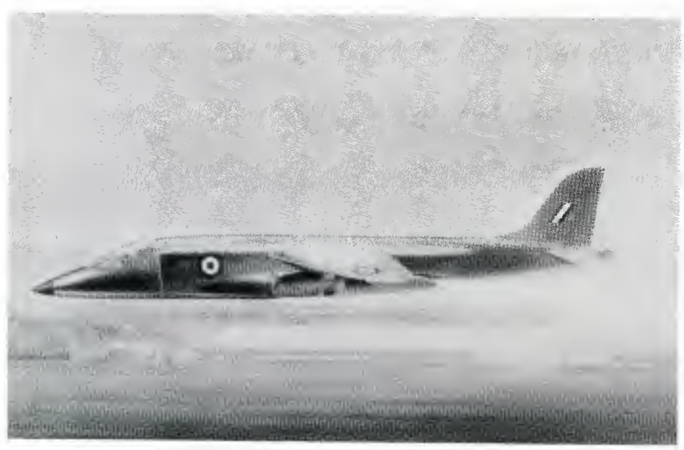
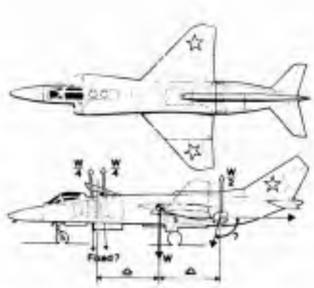


Fig. 19 P.1154 - 40% built (cancelled 1965)



	YAK 36	Harrier
Engine(s)	Turbojet	Turbofan
SFC	1·1–1·2	0·67
Hover fuel flow		
% AUW/min	2·5	1·2
% int. fuel/min	7–8	4
Transitions		
avge accel/decel	1/6g	1/2g
STO?	NO	YES
Ski-Jump?	NO	YES
VIFF?	Barely?	YES
I.R. SIGNATURE	STRONG	Stealthy

Fig. 20 Lift engine + V.T. engine : YAK 36 Forger

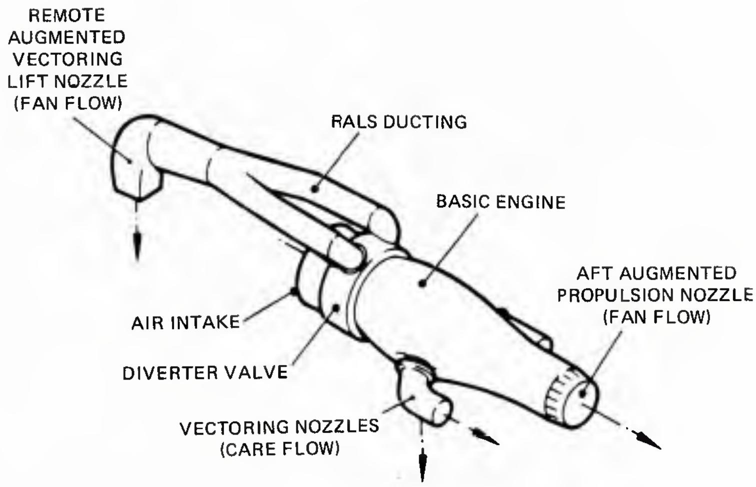


Fig. 21 RALS

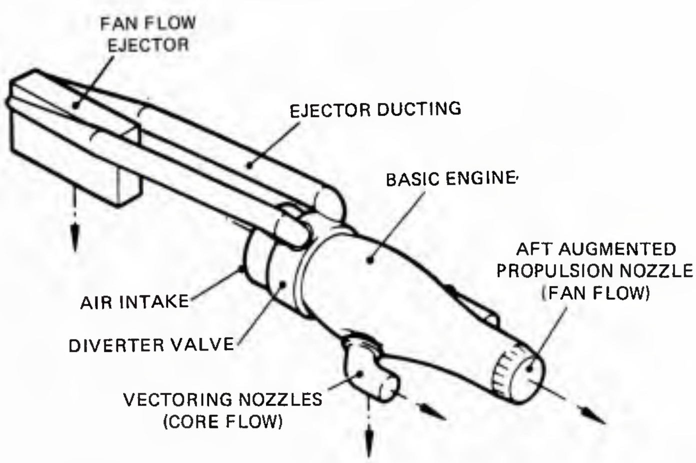


Fig. 22 Separate flow ejector

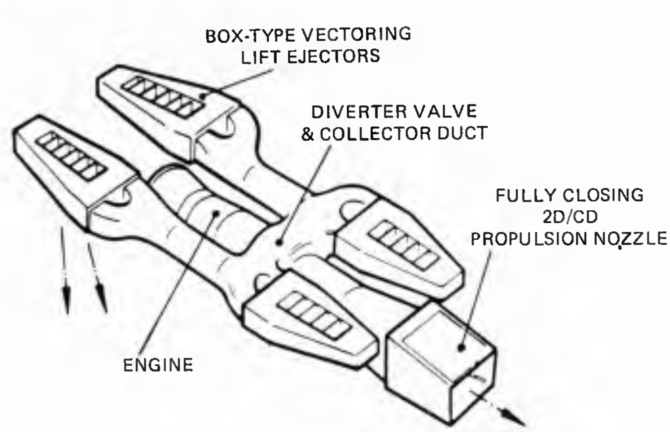


Fig. 23 Mixed flow ejector

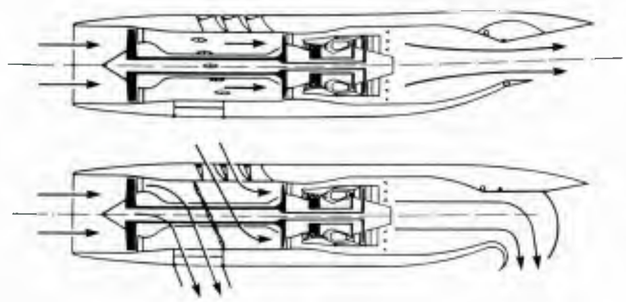


Fig. 24 Tandem Fan

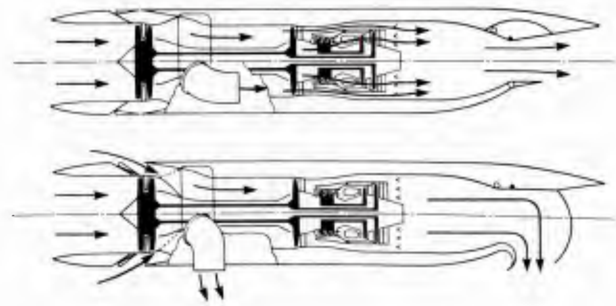


Fig. 25 Hybrid Tandem Fan

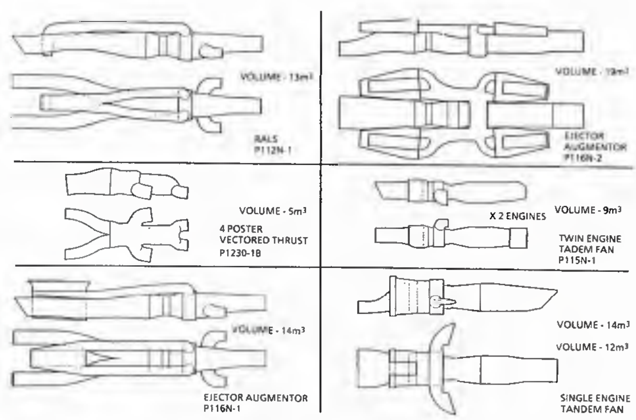


Fig. 26 Power Plant Volumes

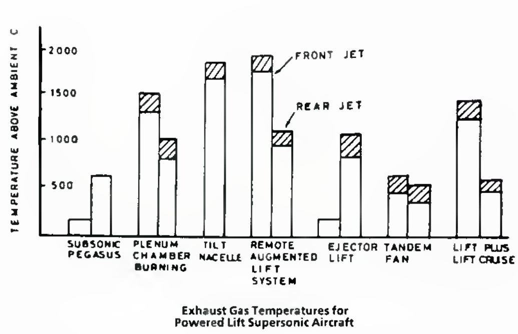


Fig. 27 Exhaust Temperatures

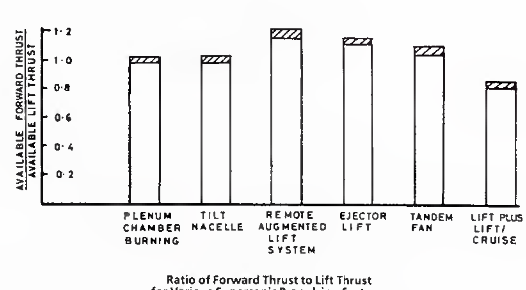


Fig. 28 Propulsive Thrust / Weight

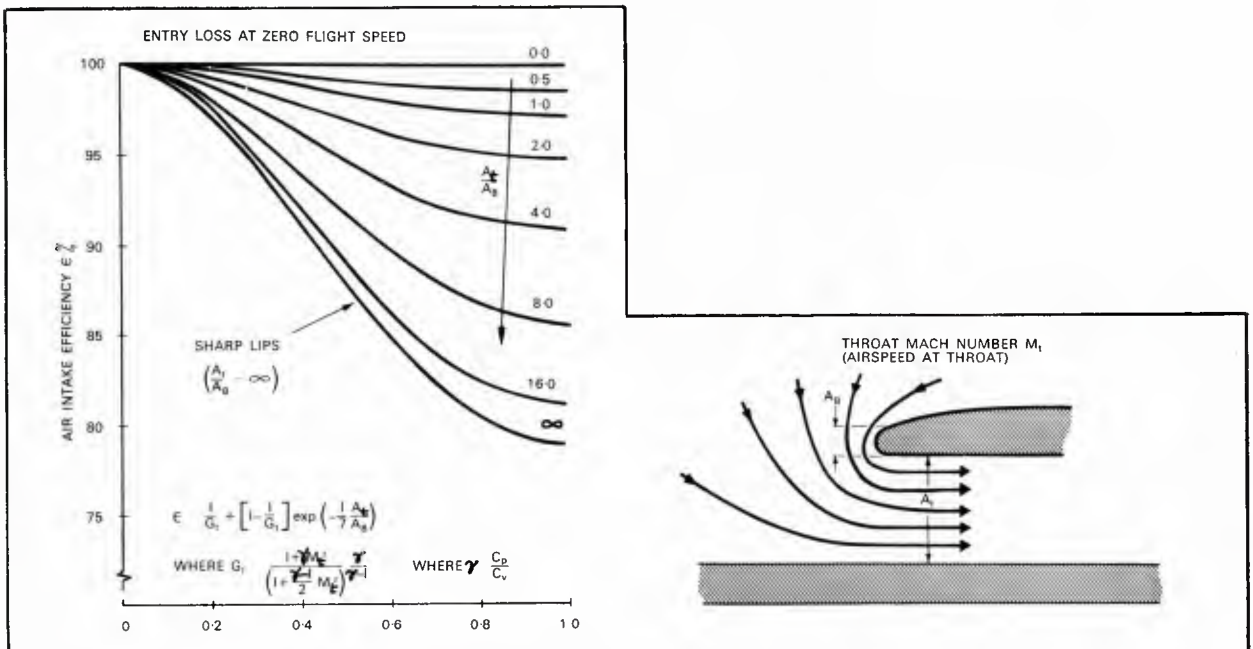


Fig. 29 Air Intake Efficiency

Fig. 30 Multijet Ground Fountain

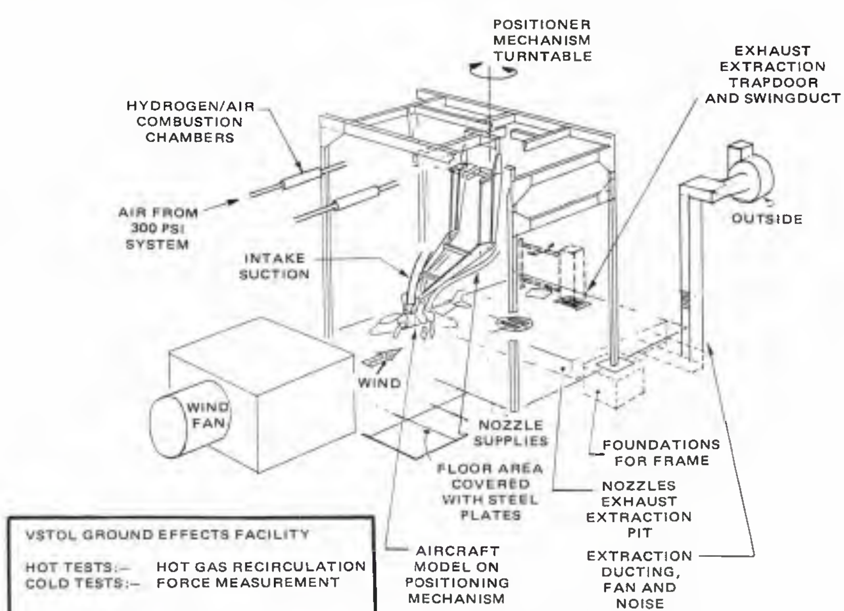


Fig. 31 Hot Gas and Ground Cushion Facility

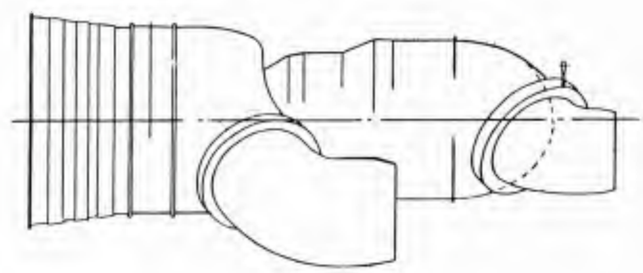


Fig. 32 "Droop and Trail" nozzle arrangement

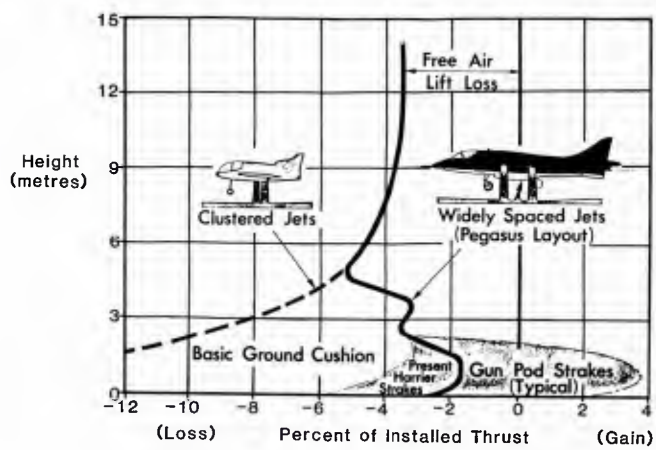


Fig. 33 Suckdown and Ground Cushion

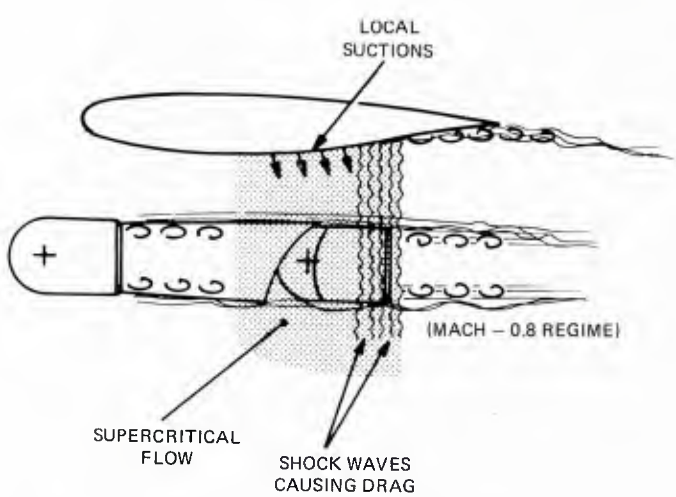


Fig. 34 Local underwing suctions

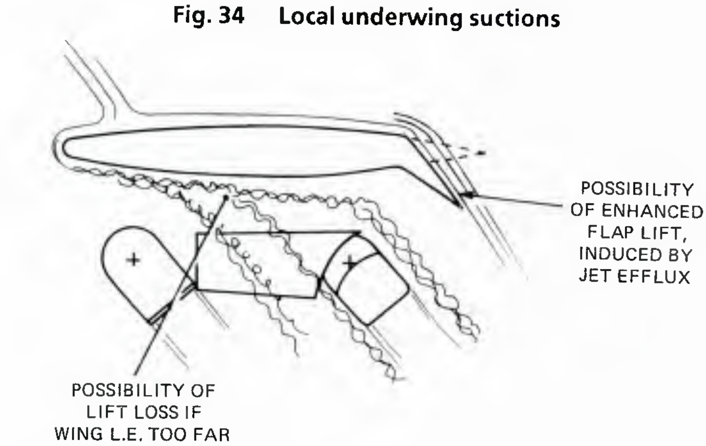
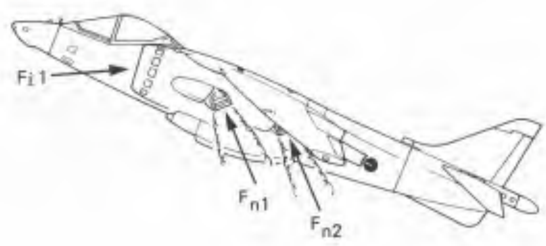


Fig. 35 Supercritical flow under thick wing



THE STREAMFORCE ON THE INTAKE (Fi) IS EQUAL TO THE MOMENTUM DRAG.
THE STREAMFORCE ON THE NOZZLES (Fn) IS EQUAL TO THE GROSS THRUST.

Fig. 36 Forces on air intake and nozzles

ADVANCED FIGHTER DESIGN

Operational Experience and Future Requirements

by : Cdt.Avi Ir D. AGNEESSENS

SERVICE des ESSAIS en VOL
SEV/SABCA
B 6200 GOSSELIES

1 INTRODUCTION

In order to present such a broad subject, it is maybe interesting to analyse the introduction of several different aircraft in the inventory of european airforces since 1970. Having flown different types of aircraft, such as the F84F, the MIRAGE 5, the F104G and recently the F16, I can compare the possibilities they have and what is more critical, the deficiencies they show for the mission they are employed. Thus before going into the analysis of these aircraft , it is necessary to state in what role each of them will be employed. To do this, the requirements have to be considered. These are mostly imposed by NATO, but national requirements could be considered also, especially for those nations which produce aircraft. This last aspect of the problem is beyond the scope of this lecture. Usually, NATO requirements are so broad that all nations do have problems to give a correct response to them. Due to the large variety of missions to be performed, in the air-to-air (A/A) or in the air-to-ground (A/G) roles , it is evident that non specialised aircraft will be used and also low cost aircraft will be chosen because more and more often, the public opinion does not easily accept large expenditures for its defense programmes. The analysis will then be limited to the different aircraft which were or are still in use in european airforces or more generally in the european theatre of operations. This theater is very demanding due to different factors which will be underlined, such as the threat, and the weather.
The concept of "multirole" aircraft, being considered as the "ideal" choice by many, will be discussed as a response to the variety of requirements in the european theatre, especially where small nations, like Belgium, are concerned. Another point that will be discussed here concerns the pilot training in peace time. Therefore, the use of simulators, the participation in national or NATO exercises, the use of weapon ranges and the number of flying hours per year will be mentioned to indicate how it is possible to maintain a high level of proficiency for the pilots.

2 REQUIREMENTS

2.1 NATO REQUIREMENTS (FIG.1)

The opponent for NATO is the Warsaw Pact (WP). The majority of WP forces are equipped and trained for offensive operations. Given the political dominance of the Soviet Union, it is believed that the WP will employ, in case of war, all offensive resources. During the past years, the WP airforces have converted a traditionally defensive posture into one that is now increasingly offensive in capabilities. Considering only air assets, we can realize that move by seing "old" aircraft replaced by new ones having more range for the ground attack types and are more agile for the air superiority mission. They are capable of deep penetration, with more comprehensive avionics, ECM or anti-radiation capabilities. It is now evident that the whole of Western Europe is within the reach of WP airpower. (FIG 2) As an example of this, let's consider some replacements which are now in progress. The MIG 31 Foxhound is replacing the MIG 25 Foxbat for interception and reconnaissance (recce). This aircraft is capable of M=2.4+ with M=3.0 dash. The MIG 29 Fulcrum will replace combat aircraft like the MIG 21, MIG 23, MIG 27 and the SU-22 in A/A and A/G roles. The SU-27 Flanker is an air superiority fighter comparable to the F-15 and F-14. Other aircraft, namely the Frogfoot, in ground attack role, or the Blackjack, as strategic bomber or the Mainstay, as AWACS (Airborne Warning And Control System) are also entering into WP inventory. And the reaction now is the same as in the past : a constant adaptation of NATO requirements. NATO is requesting each member nation to fulfil the requirements in terms of defense of a portion of territory facing WP forces. Everything must be done to react sincerely and effectively against any potential threat, in the air and on the ground. The spectrum of requirements is thus very broad, facing nations with difficult choices. New threats are leading to new requirements and new methods of defense in NATO, and nations have to follow the trend, which very often means new equipement. This process costs money and the public does not always understand the emerging need, while the policy in WP seems easier to be imposed by the powerful Soviet Union. Nevertheless, NATO is requesting each member to fulfil its commitements and evaluations will be done each year to monitor the efforts and achievements made.

2.2 NATIONAL REQUIREMENTS

These are of the same nature as those requested by NATO : the defense of the territory. As far as aircraft are concerned, all A/A and A/G operations must be considered. Nevertheless, A/A operations are more pressing for european nations because interdiction, close air support (CAS) or recce are considered as offensive operations. That is why air superiority aircraft are given higher priority. On the other hand, budget constraints are such that only a few nations, wealthier nations should I say, can afford different types of aircraft, which can be optimised for one role each. In general, in european countries, defense expenditure must be kept to the minimum, which means a constant amount of money each year in constant terms, whereas the WP has an increasing financial effort dedicated to its defense budget. Due to the fact also that the trend in cost of new technologies is not favourable, that development costs are increasing and that the break-even point is reached only for long production runs, the prices are so high that most nations are faced with the choice of one type of aircraft which will be used for multiple tasks : a multirole aircraft.

2.3 THE IDEAL CHOICE

We have seen how broad the requirements are. Before going more deeply into the problems, I shall indicate the categories of aircraft which have so distinct characteristics and different possibilities in A/A or A/G operations.

2.3.1 AIRCRAFT CLASSIFICATION

2.3.1.1 Fighter interceptor

Is used against a non manoeuvering target and generally directed towards it by a ground control radar. High speed, high longitudinal acceleration, high altitude and long range performance are required. Long range, all altitude missile armament and associated radar is required.
The aerodynamic design is dominated by the need for low profile drag and low wave drag.
A typical aircraft of this category is the F104 Starfighter.

2.3.1.2 Air Combat Fighter

Is used against manoeuvering target and will meet its opponent by radar vectoring from the ground, or by independant search and steering. After an initial pass, if unsuccessful, a dogfight can develop, usually in visual range, at low or medium altitude. This is why high supersonic speed is not required, but the best possible sustained and instantaneous turning performance is essential. Short and medium range missiles and gun armament are carried.
The aerodynamic design is dominated by the search for low induced drag at high G's and by the need for good departure characteristics as the dynamic stall is approached.
A typical aircraft of this category is the F16.

2.3.1.3 Ground Attack Fighter

Operating primarily at low altitude, and with less emphasis on

turning performance, the wing loading can be much higher. This is usually the case because of the amount of external stores being carried. There is no need for supersonic performance but the design should emphasize a store carriage arrangement and a drag at high subsonic speed which do not ruin the aerodynamic efficiency in cruise configuration, e.g. on the way to the target.
A typical aircraft of this category is the Tornado.

2.3.1.4 Reconnaissance Fighter (Recce)

The general requirements are the same as for Ground Attack Fighter, but less emphasis is made on external carriage of stores. Usually, there is no specific aircraft designed for recce operations only, and the equipment is fitted in an existing airframe modified for this role.
Low drag at high subsonic speed is the general feature of such an aircraft.
A typical aircraft of this category is the F101 Voodoo.

2.3.2 GENERAL REMARKS

i) Since WW II, fighter aircraft have traditionally been converted from aircombat to ground attack or fighter bomber role, usually by putting a wide variety of external stores which make a"flat iron"from a valuable aircraft. Only few aircraft have avoided that unpleasantness, as in the UK the Hunter and the Lightning P1, in the USA the F-102 or the F-106, or in France the MIRAGE F-1, most probably because it was not cost effective. But all other aircraft have seen their potential developed also in the air-to-ground role. The case of the F 104 Starfighter is typical : designed initialy as an interceptor, that aircraft was also used by different nations as a G/A asset, for deep and high speed penetration, in the "strike" role (delivery of a nuclear weapon). Belgium, for instance, used the F 104G in both A/A and A/G missions, with good results. So in fact, many aircraft can be used to some degree as multi-role fighters, depending mainly on the equipement fit. Usually, aircraft intended for the european theater of operations, with the smaller member nations of NATO, were air combat fighters with good capability for external stores carriage. Let us note that the increase of the wing loading is desirable to improve the low-level ride qualities of an air combat fighter and also the aiming accuracy in turbulent air conditions.

ii) The second remark is a consequence of the previous one. Several nations in NATO have a modest internal product per inhabitant. Expenses for defense are not popular in most democracies. The result is that the total amount of money is the only parameter which is significant for the public opinion, without considering other factors, like the effectiveness, or the overhaul or simply the costs of the operations. The result of this is that very often, one type of aircraft is employed in different roles, the pilot being expected to do his best to overcome the deficiencies of the aircraft with regard to some of the missions. The only possible choice is very often a single seat, single engine aircraft, tailored to the air combat due to its dimensions. A compromise is then necessary for other missions and it can become difficult to satisfy defense needs.

2.3.3 COSTS OF FIGHTER AIRCRAFT

It is already evident that small nations will avoid too specialised aircraft such as the A-10 or the HARRIER, because of the complex requirements they are faced with inside NATO. These requirements being considered, each smaller nation is going to chose a single aircraft. But this choice must be done not only as a function of the flyaway price, but also considering the costs for the operations and the support, certainly in peace time, and perhaps also in wartime. It is apparent that a balance must be found between wartime operations and peace time constraints. This fact is very sensitive for small nations in NATO, and we will see how different factors can affect what is usually called the flyaway price and both the operations and support (O&S) costs.

2.3.3.1 Flyaway costs

These costs include Research and Developpment (R&D), initial production of the weapon system, including the equipments, and the profit of the manufacturer. For nations which do not develop an aircraft, these costs appear as a lump sum in the defense budget. Therefore they are very sensitive for the public opinion, and to make them acceptable, a system of direct and indirect compensations for the industry is required. This is generally so for small countries like Belgium. For other countries, which are capable of developing and producting a fighter aircraft, these acquisition costs are very often better distributed over time by an early commitment of the Ministry of Defense. Nevertheless, costs are of course increasing in the same direction as the overall size of an aircraft, simply because it takes more working hours to assemble a big aircraft. The experience shows that a single engined aircraft is less expensive and smaller than a twin engined one. Small nations will thus be attracted by the unit cost, and better standard of equipment may be posponed until money is available again.

2.3.3.2 Operations and Support costs

These represent about 50% of the total costs for an aircraft, and approximately 40% of the total manpower available. It is thus important to consider them and to analyse the following cost drivers:

- logistics maintenance level and supply
- facility and spare parts locations
- manpower skill and productivity
- number of systems to be serviced
- system characteristics and complexity
- system inspections and tests required
- system flying time and reliability
- type and quantity of service to be delivered
- etc...

On this last aspect of the problem, it is accepted that fuel consumption is representing about 7% of the total O&S costs. Those costs are very sensitive and cannot be controlled, especially when the fuel is expensive, as happened in the recent past. The tendency, and the danger, is then to reduce the amount of flying hours for the pilots, inducing other problems of training or safety. Fuel consumption is of course to be considered and is proportional to the size of the aircraft. On that aspect, small aircraft are less expensive. But fuel is not the only aspect to be considered. If the aircraft is very small, it may be difficult to modify it for a mission, to fit in due time the necessary equipment, or to survive a defense protecting a target. If the aircraft's load carrying capabilities are too modest, several aircraft may be needed to perform the mission a single aircraft could accomplish alone. On the other hand, if the aircraft is big, the tendency will be to carry each time unnecessary equipement, which adds weight and thus increases fuel consumption. Here again, a compromise must be made according to the military requirements.

2.3.4 ADAPTATION OF FIGHTER AIRCRAFT

It is clear that new technologies can improve the O&S situation, but it is also recognised that the best moment to apply those new technologies is in the initial concept. This causes a higher flyaway cost, but usually reduces the O&S costs. Considering old aircraft, why not apply new technologies to update them? This is necessary not only due to the continuous changes in mission requirements, but also because they can reduce the O&S costs and also the logistic process during remaining years of operations. A permanent monitoring of the distribution of the costs is necessary to give a possible improvement in some fields. Each field can be studied independently, to see where expenses are made and where savings are possible.The different fields and the structure of a particular one are given in FIG 4.

2.3.5 FIGHTER AIRCRAFT MODIFICATION

As already mentionned, the trend is to choose an aircraft which is capable of performing a variety of missions, a multirole aircraft. But the operational requirements, which lead to its definition, are very often inconsistent. Ground attack missions are very complex for a number of reasons : threat environnement and density, navigation NOE (Nap On the Earth), weather, turbulence, etc... So, if the aircraft was designed primarily for A/A operations, which is usually the case, the equipement used will have to be very sophisticated. Due to the reduced space available, they will have to be very compact. These two characteristics render equipment very expensive. It is well known that prices increase in inverse ratio to the size. In fact, the development costs of an aircraft are affected by the requirements, and if those are complex, costs will increase and there is no limit in R/D costs. This is especially the case when the size of the aircraft is kept to a minimum, for air combat reasons, like the radar signature or simply the visual magnitude. If the space available inside the aircraft, or in the cockpit, is very small, costs of R/D for equipement integration will increase. It is interesting to see what are the guidelines for both A/A and A/G operations.

2.3.5.1 AIR-TO-AIR OPERATIONS

The keypoint seems to be the manoeuvrability, and the agility of the aircraft, which results from a combination of manoeuvrability and performance. But manoeuvrability needs good handling qualities, particularly at high angles of attack, with good resistance to spin or departure. The flight envelope must be as wide as possible, and its boundaries must be reached without difficulty, even if some external loads, like A/A missiles, are carried. Attainable pitch and roll rates are important factors for the effective manoeuvring. We are familiar with the FIG 4 where a flight envelope is represented. In this, what can an aircraft do in terms of instantaneous or sustained manoeuvres? The answer is given by another chart, where Ps (Specific Excess Power=SEP) contours are given , for a given number of G's, at a given speed, and indicating the resulting turn radius or turn rate. See FIG 5. Historically, it is a fact that the best fighters had high thrust/weight ratio and moderate wing loading. Also the wing span was moderate for evident structural reasons, which is requiring a compromise with the preceding requirement. Emphasis was placed on turning performance, both instantaneous and sustained, although agreement is not unanimous on which is the more important. There are several contributing factors, such as (the following list is only indicative and not exhaustive):

- pilot G's tolerance devices or techniques
- optimization of handling qualities to make the aircraft safer at the edge of the flight envelope, by the use of fly-by-wire for instance
- adaptation of the engines for the task

We will see how these requirements were realised on different aircraft.

2.3.5.1.1 G tolerances

Most pilots are equiped with anti-G suits plugged to the aircraft. This equipment is absolutely necessary on some aircraft, because of the capability they have to sustain high G's. For some other aircraft, the capability of getting instantaneous G's, limited to the maximum load factor for structural reasons, is also requiring an anti-G equipment which must match the onset of the loading generated by the aircraft. For instance, on the F 104 Starfighter, and on the MIRAGE 5, the limit of 6 G's cannot be maintained in stabilised flight, and cannot be exceeded for structural reasons. On the F 16, it is possible to sustain 7 G's, and reach 9's, so that induced loss of consciousness is possible. To minimize such a problem, the design of the cockpit was studied so that those physiological limitations would place a lesser constraint. The inclination of the ejection seat was set at the best value. By doing this, other problems arose, related to the front panel depth, the space available on it, and the difficulty to reach any command and control on the panel and the non relaxed position of the pilot in flight. The F 16 has the seat with the largest tilt, at an inclination of 30 degrees. However problems of very rapid increase in G's are also encountered on the F 16, just because the inflation of the G suit is not fast enough, and does not match the agility of the aircraft.

2.3.5.1.2 Handling qualities

Manoeuvrability is a must, but handling qualities, although rarely discussed by the operational pilot, are also mandatory. Even with the use of Stability Augmentation Systems (SAS), rather limited excursions in the longitudinal static stability are permitted. And a compromise between stability and manoeuvrability is still necessary. The aircraft response must remain good at very high angles of attack and the pilot must keep confidence in his aircraft up to the incidence limit. This limit is rather low on certain aircraft, and the use of incidence meters is generalised, with sometimes a coupling to the stick,as on the F 104 where a shaker and a kicker prevent catastrophic situations at the incidence limit. On the F 16, the Flight Control Computer (FlCC) is limiting the aircraft to 27 degrees AOA (Angle Of Attack). Beyond that point, a catastrophic situation could occur , a deep stall, which means the loss of the aircraft. In roll also, the stability must be assured, because the aircraft must be directed by the pilot, to follow a precise trajectory, and also for safety reasons. Each manufacturer is indeed giving a maximum rate of roll not to be exceeded for structural reasons. Low stability could deteriorate the possibilities to respect those limitations. Here again, a compromise is necessary, between stability and the need of to have rapid roll rates changes in combat.

2.3.5.1.3 Engine(s)

We have already stated that thrust to weight ratio is the most important factor, for different reasons which, although evident, we state once more the agility of the aircraft, the sustained turn performance, the best take-off characteristics, and so on.... In general the faster the velocity vector can be changed, in direction and in magnitude, the better the aircraft performance. This means that another factor must be considered: the overall time it takes to get the desired thrust. The transient characteristics are very often forgotten by the manufacturers, and they stress the attention of a potential buyer on parameters which are easy to explain, such as the net thrust or the Specific Fuel Consumption (SFC), but rarely on the transient characteristics, which are so important in combat. Usually, the time needed for acceleration of the engine is long enough to enable the hydro-mechanical fuel control to do its job, with some help of the pilot for difficult cases. This is the case for the ATAR 9C of the MIR.5 aircraft, and the pilot must handle the engine with care, and monitor the EGT (Exhaust Gas Temperature) during any fast throttle movement. But it is also the case for the PW F 100 of the F 16, in certain areas of the flight envelope. Here again new technologies, with the pick-up and the analysis of a greater amount of parameters, will help the task of the pilot at a moment where his attention is totally absorbed on the combat. SFC is also important but will be discussed in the A/G analysis.

2.3.5.2 Air-to-Ground operations

In the A/G role,it is generally accepted that the aircraft must be very manoeuvrable, because of the necessity to fly close to the ground in an environnement where the threat density, the meteorological conditions and the target are in permanent evolution. But the need of manoeuvrability is not comparable to the one required for A/A operations, where high AOA (Angle Of Attack) have also to be considered.
We will discuss the problems with the wing loading (W/S) as an entry parameter. There is no clear requirement for W/S value, but it is a matter of fact that some manoeuvres must be possible in regions of rather hilly terrain with a high density of threats. This manoeuvre could be a sort of sinus shaped contour with an amplitude of 30 meters and a wavelength of 1200 meters. FIG.6 is giving such a presentation for 2 different values of W/S and a CLmax = 1. It shows that below a certain speed, for the higher W/S value, the aircraft is not able to follow the contour. Speed or more precisely lift curve slope is also an important parameter.

2.3.5.2.1 High wing loading (W/S)

When an aircraft requires more lift, thus more AOA, than another one, for the same speed, the tendency of the pilot is to act in greater anticipation, because it will take more time to get the necessary AOA. This is the case whenever the W/S is high. On the other hand, the lower the aircraft is flying, the lower the speed must be. It is a known fact that with the speed, the average altitude above terrain depending on pilot experience increases in manually flown low level missions. Low speed also requires a low W/S. Both requirements, high manoeuvrability and low speed, are inconsistent with the need to carry armament, most of the time as external load, which makes the W/S higher. Some aircraft, such as the F 104G had an initial W/S of about 150 lbs/ft2 and a final W/S of 200 lbs/ft2 with external loads at max. gross weight. And the first value was already requiring a speed of 450 Kts in order to follow the previous contour! Because of the danger of a possible high speed stall, which is catastrophic at low level, anticipation is necessary. Needless to say that an aircraft like the F 104G was not suited for terrain following. But that aircraft was very good for high speed penetration, due to its lazy response in turbulence. In terms of air combat, the W/S is predominant, together with, of course, the Thrust-to-Weight ratio (T/W), to assure a good turn rate. Unfortunately, the same W/S ratio is also predominant in the response to turbulence, but in the opposite way. There is thus a conflict between the requirements for a large span, to maximize sustained turn rate, and a small span to minimize the response in turbulence. This leads to a very difficult compromise for a fixed wing aircraft, but can easily be solved for a swing wing aircraft, at the expense of the greater complexity of the latter.

2.3.5.2.2 Lift curve slope

The W/S ratio is not the only parameter to consider in the ride characteristics of an aircraft in turbulence. The lift curve slope is also important, because it is a characteristic of the effectiveness of the wing and shows how good are its lift-generation capabilities. For instance, MIR 5 has a lower W/S ratio than the F 16, but for the same speed, the lift generated by the wing of an F 16 is higher. That is the reason why a MIR 5 is more confortable than the F 16 in turbulence, but the latter is easier to fly because of the slower speed needed, enabling the pilot to stay at low level.

2 2.3.6 FUTURE NEEDS

The aim of this chapter is to give some guidelines for aircraft improvements, or eventually for future aircraft. The emphasis is put on possible updates, taking into consideration the present capabilities of aircraft in NATO and more specifically in Belgium. The future needs are in fact resulting from the shortcomings of existing aircraft as found in operations. Some of those shortcomings are common to all aircraft , others are specific for A/A or A/G operations.

2.3.6.1 Common requirements

2.3.6.1.1 STOL capabilities

With present aircraft ,such as the F 16, the Thrust-to-Weight ratio available permits take-off on rather short runways. But a long runway is still necessary for landing, due to a number of factors, the most important of them being the approach speed and the weather. An important improvement is the adoption of high lift wings, making possible lower speed in approach, complemented by the use of better braking systems, reversers, braking parachutes or brakes. But the landing distances are still too long. Why not use other systems, like arresting gears?

2.3.6.1.2 Operations from semi-prepared surfaces

Operations from semi-prepared surfaces could be envisaged with some existing aircraft. But to do this, two distinct problems must be solved : adaptation of the landing gear and the engine protection against FOD (Foreign Object Damage). The adaptation for the first requirement is no problem, existing technologies make this very possible, and the problem could be solved for different situations like take-off and landing. But for the second requirement, it is not evident that a technical solution exists for present fighter engines. The problem posed by bird strikes in day-to-day operations seems insoluble.

2.3.6.1.3 Cockpit layout

It is evident that the cockpit should be optimised for one of the missions, in A/A or in A/G. It seems rather difficult, due to the space available for the pilot interface systems, to have both together, unless MFD (Multi Function Display) are used. Even for the F 16, which tried to achieve the best compromise between A/A and A/G, there are shortcomings, not only in the performance of some equipement, but also in the lack of other items, like situation awareness devices, which differs from one role to the other. Multiple Function Display (MFD) are more and more used, enabling the pilot to select different sets of information necessary at a particular moment, for a particular phase of the mission, but the intervention of the pilot is still needed to state what he wants. Artificial intelligence will alter this process in due course. In any case, a problem of pilot workload already exists. The trend being to operate small aircraft, which cost less, the pilot will be alone on board to do everything : fly and think. Even if aircraft are easy to fly, the workload will remain substantial. That problem has been solved differently by some manufacturers, by having two men on board to share the job. On the F 16, the optimisation of the avionics was the answer. In A/A role, several weapon delivery modes are possible, using guns or missiles, all of them directed by the FCC (Fire Control Computer) which takes the information from other systems like the Radar (RDR), the INS (Inertial System), the SMS (Store Management Computer) or the HUD (Head Up Display) and are selected by the pilot via the stick or the throttle, which allows an head-up flight. The same happens in A/G, where the FCC is controlling the same elements for another task, and CCIP (Continuously Computed Impact Point) or DTOS (Divetoss) in visual mode or CCRP (Continuously Computed Release Point) or LADD (Low Angle Delivery Drogue) in blind mode are possible. All these possibilities are always present, with priorities for the air combat modes, because the aircraft was optimised for them, the software of the FCC enabling the pilot to choose any time the mode he wants to operate. Its versatility is thus dependent on the quality of the software installed.

2.3.6.2 A/A requirements

2.3.6.2.1 Size

The small size of an aircraft is an advantage for different reasons, but the most important is its signature. Radar signature is important, and a lot of research is being done to improve stealth characteristics. But visual signature is also important. In fact, most of the critical phases in air combat happen in visual ranges. In order to maximise the chances of survival of an aircraft in an air engagement, an action is to be taken as soon as possible, not only when the aircraft has been detected by the radar, but also when it has been identified by the pilot. Identification is one of the major problems nowadays and there is an urgent need to give the pilots systems to identify the opponent. It is possible to visually acquire an aircraft at 4 NM, but it can only be identified at 2 NM. The time lost is dependent of the size of the opponent, but also on its camouflage. Needless to say that smokeless engines are essential.

2.3.6.2.2 All around visibility

The systems and the sensors can be very sophisticated, but nothing can replace the human eye, and the high capability of the human brain to exploit the information, combined with the skill of the pilot and the operator in the aircraft. It is thus essential to give the pilot the possibility to look all around. He can be helped by systems which give him a good situation awareness, but the final outcome in a dog-fight, will depend on what he sees.

2.3.6.2.3 Other requirements

Some of them were already discussed in a previous chapter such as G tolerance, handling qualities or engine performance.

2.3.6.3 A/G requirements

2.3.6.3.1 Pilot workload

As previously said, A/G operations are very complex, thus very demanding. Most of the combat aircraft assigned in A/G operations are dual seaters, like the F 4, the F 111 or the MRCA. Some others are not, like the F 104G, the MIR 5 or the F 16 and F 18, and the next generation of multirole aircraft is single seat also. It is a matter of fact that to solve the problem of workload, a second operator is an advantage, and it is a must when integration of the different systems is not automated. If a dual operator is not possible, the integration must be studied carefully.

2.3.6.3.2 External loads capability

The kill probability of a target depends, among other factors, on the amount of munitions fired at it.The need exists then to carry numerous munitions. Suspension capabilities, and the maximum weight of external stores that can be carried, are very important. For instance, the F 16 has 9 suspension racks, with a total capacity of 15200 lbs and with full internal fuel, it can still carry 10500 lbs of external stores. The external loads are of course increasing the total drag. The need is thus to reduce the drag, by having conformal external stores, and also to have better engines, by reducing their SFC.

2.3.6.3.3 Situation awareness

It is a necessity to keep the pilot aware of what is happening around his aircraft, not only about potential threats, but also about his friends. Tactical situations are so complex that all the information should be processed before being presented to the pilot. Therefore a good software must be used, and for each segment of the mission, priorities must be defined, with limited possibilities to alter them in flight. And the way all this information will be presented to the pilot must be carefully defined.

2.3.6.3.4 Other requirements

Where high speed low level flight is concerned, crew confort is a must. That means that the size of the cockpit is important, but also the noise from the conditioning system, which is usually too high, must be kept to a minimum. The ejection capabilities must also be good, which means a high performance ejection seat. The flying equipement must be very reliable, so that it never becomes a problem in flight.

3 TRAINING

Combat pilot readiness concerns all the airforces,especially in peace time where the proficiency level is usually reduced.In order to maintain a "mission ready" status, on the first day of conflict, a training program is necessary, which should be performed on an aircraft as close as possible of the one used in operations. We will not discuss the problem of initial qualification of a pilot, but only the problem of continuation training. To achieve this, 2 means are used, which are complementary : participation to exercises and the use of flight simulator.

3.1 EXERCISES (FIG. 1)

They mean live flying, in a scenario which is as realistic as possible. Therefore, different simulated threats are used against friendly forces. In Central Europe, most of the exercises and manoeuvres are organised by COMAAFCE which directs the employement of Allied Air Forces, taking into account the directives and guidelines of SHAPE. It is a fact that due to the permanent change in the situation, namely the WP threats, the request of major commands, like COMAAFCE, is to have very versatile aircraft which can do offensive and defensive operations. The need is thus for a multirole aircraft. In the A/A role, groundbased and airborne personnel is to be trained together and the assessment of the mission should be done jointly. Video cameras are used, and the parameters are taken from the HUD, which is very helpful. But the complete scenario of a simulated combat is still difficult to assess, specially when several aircraft are involved.
In the A/G role, the assessment is easier because most of the important factors can be filmed through the HUD. Nevertheless, it would be very interesting to have also a sort of post attack assessment, i.e. to film the damage resulting from the attack.
Training of aircrews is also done on firing ranges, where dummy or live munitions can be used. The result of the attack is immediately given to the pilot. Later on he can also assess the film and explain the result on the range.

3.2 SIMULATORS

For continuation training, simulators are used, including, among other types, the Mission Simulator. With the advent of ever increasing levels of system integration, which reduces the amount of switchology, there is an urgent need to know exactly the function of each 'switch. To learn this, it is cost effective not to use expendables, like fuel or weapons, but to use simulators, which can duplicate the entire mission, from engine start to shut down, with particular emphasis on certain mission tasks which cannot be accomplished in flight. The cockpit layout, the hardware and the software must be identical to the one of the aircraft, and there is no need, in my opinion, to have any kind of motion simulation. But the imagery must be very comprehensive and of good quality.

3.3 FUTURE NEEDS

There are of course major differences in training A/A and A/G operations, but both of them require a certain amount of actual flying, considered as a minimum, and the NATO requirements are rather strict on that point. A pilot's job is to fly, on whatever is available, from high performance aircraft to gliders. The request is thus evident : keep them flying!

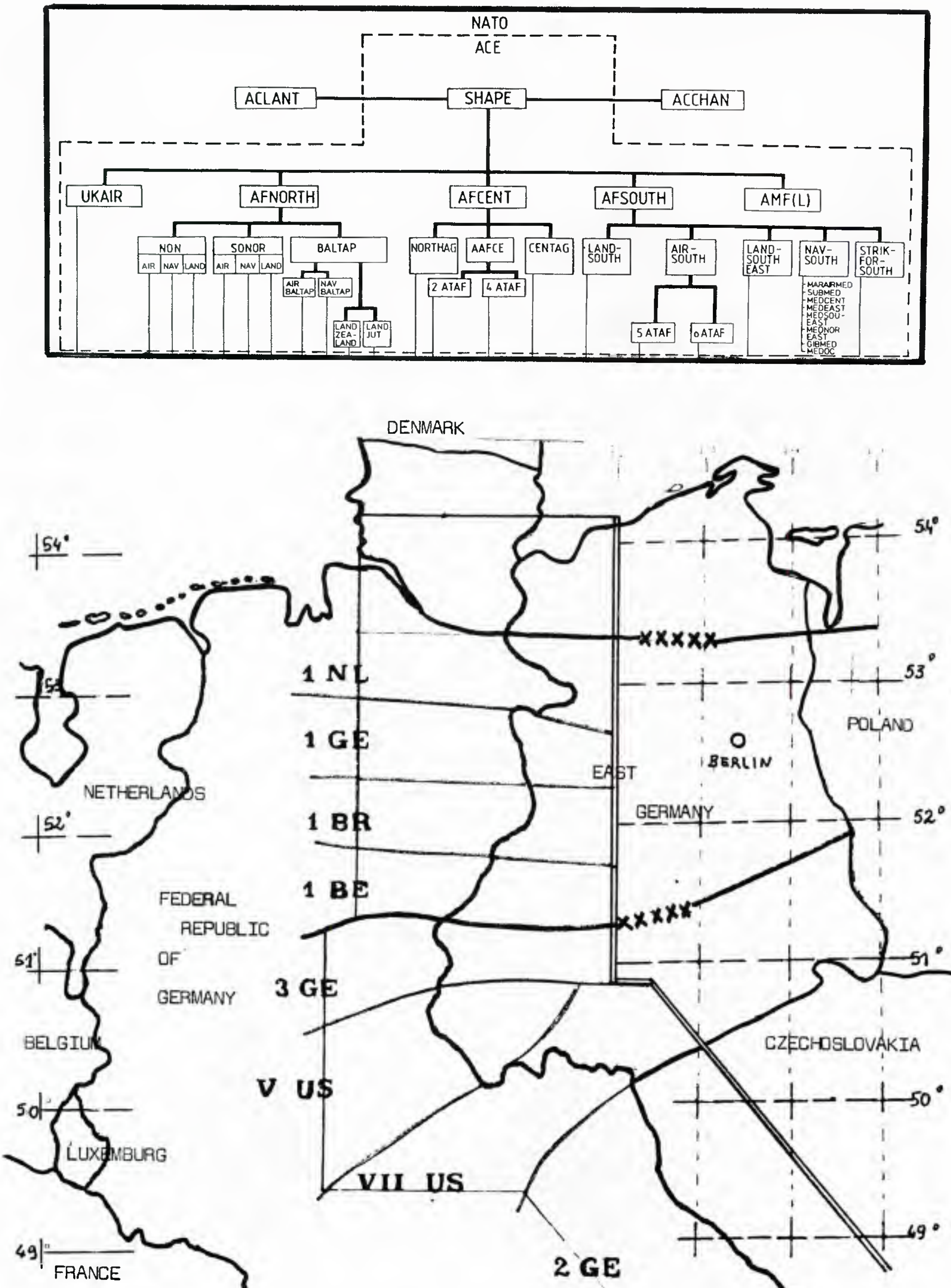


FIG.1: NATO IN CENTRAL EUROPE

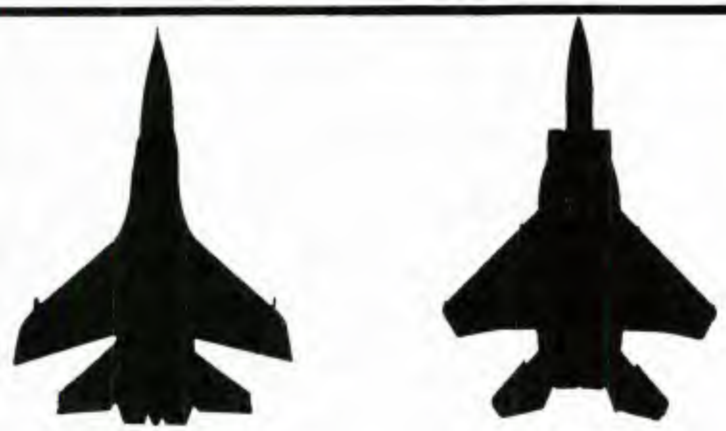
MiG-29 FULCRUM F-16

MiG-29 Fulcrum et F-16 Fighting Falcon

	MiG-29	F-16A
Dimensions		
Envergure	10,25 m	9,45 m
Longueur, sans tube Pitot	14, 7 m	14,1m
Surface alaire	34,4 m²	27,86 m²
Masses et charges		
A vide, avion équipé	7800 kg	6575 kg
Carburant interne	4500 kg	3175 kg
Charge externe maxi.	4000 kg	4760 kg
Maxi. au décollage	16 500 kg	15 000kg
Charge alaire	480 kg/m²	538 kg/m²
Rapport poussée-poids à la masse de combat	1,4:1	1,2:1
Propulsion	2 Toumansky R-25	1 P&W F100
Poussée sans PC	55 kN	64,4 kN
Poussée avec PC	73,5 kN	106 kN
Performances		
Nombre de Mach maxi.	2,2–2,3	2

Su-27 Flanker et F-15A Eagle

	Su-27	F-15A
Dimensions		
Envergure	14,5 m	13,0 m
Longueur hors tout	20,5 m	19,4 m
Surface alaire	64 m²	56,5 m²
Masses et charges		
A vide, avion équipé	15 000 kg	12 700 kg
Carburant interne	6500 kg	5260 kg
Normale au décollage, mission air-air	22 500 kg	18 100 kg
Charge alaire	352 kg/m²	320 kg/m²
Rapport poussée/poids à la masse de combat	1,27:1	1,32:1
Propulsion	2 Toumansky R-29?	2 P&W F100
Poussée sans PC	70 kN	64,4 kN
Poussée avec PC	125 kN	106 kN
Performances		
Nombre de Mach maxi.	2,3–2,4	2,3



SU-27 FLANKER F-15

FIG.2: EXAMPLES OF USSR RESPONSE TO AIR ASSETS

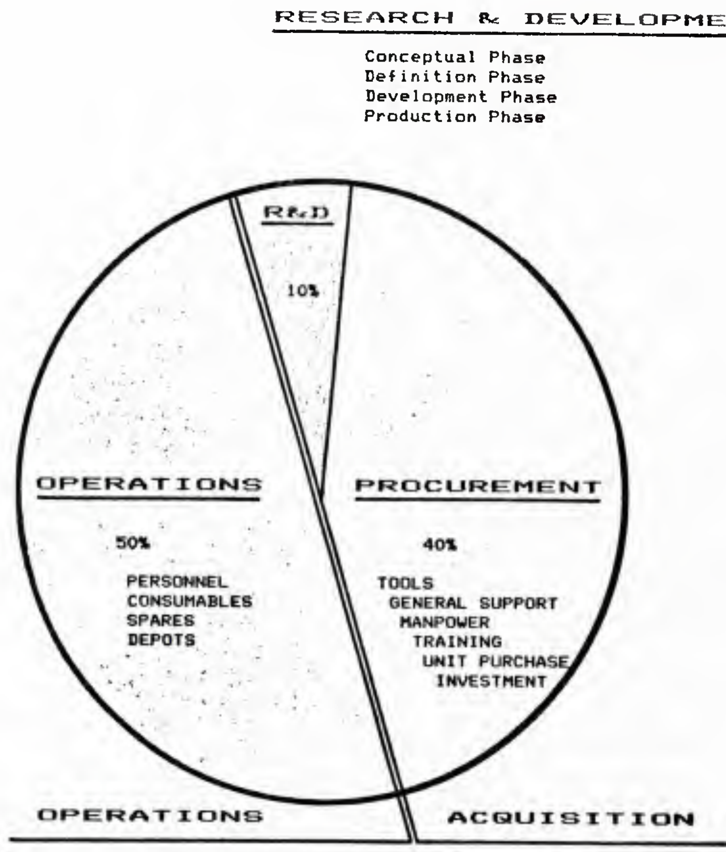


FIG.3: MAIN COSTS DRIVERS

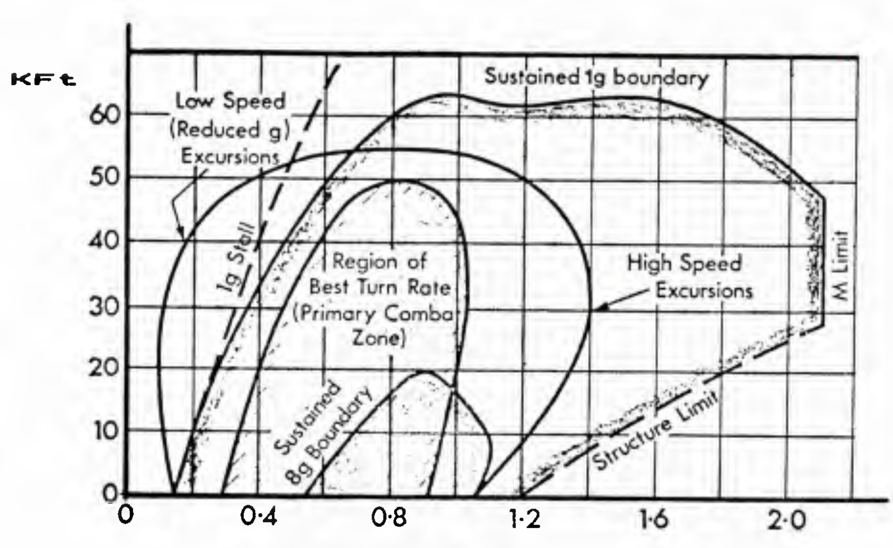


FIG.4: COMBAT ZONES

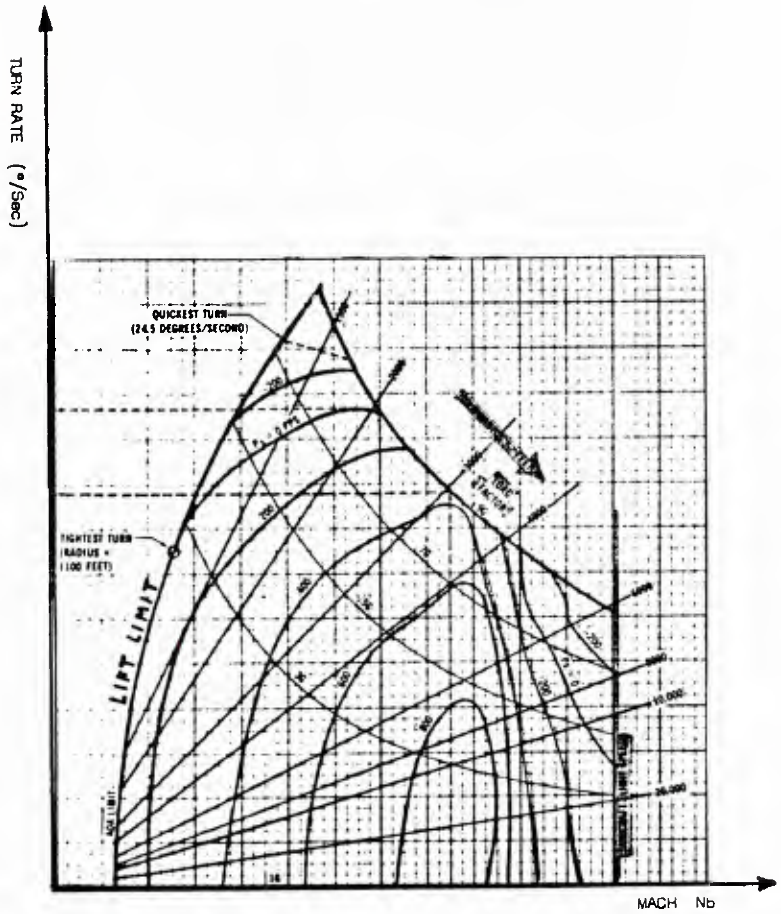


FIG.5: EXAMPLE OF COMBAT CHART

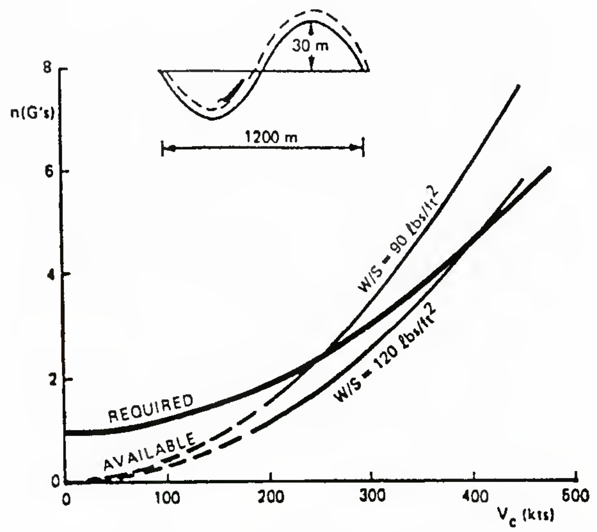


FIG.6: MANOEUVRABILITY REQUIREMENTS

THE INTEGRATION AND OPERATIONAL SUITABILITY OF EMERGING TECHNOLOGIES FOR FUTURE FIGHTER AIRCRAFT: A PILOT'S PERSPECTIVE

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SUMMARY

The tactical air mission has become extremely challenging and complex due to improvements in ground defenses and sophistication of opposing threat air forces. To fight, survive, and win in this demanding environment, we must ensure we develop the capabilities needed by our tactical pilots to successfully counter the threat.

Technological developments have fostered a host of new capabilities for application to future aircraft. This paper provides a pilot's perspective on the development, integration, and application of these emerging technologies for the air superiority mission. Of real concern is determining which capabilities will be most useful to the pilot, yet not overload or exceed his capacity to perform. Assessments will be based on personal experiences in combat, in flight testing applications in current fighter aircraft such as the F-15 Eagle, and on plans for incorporation in future fighter aircraft.

The pilot/vehicle interface and enhanced pilot performance will be the central focus, conditioned by operational suitability. Key factors will include information or task saturation, situational awareness, physiological limitations, and cockpit designs. The concept of Fighter Battle Management will be introduced and discussed as a framework for evaluating and integrating future capabilities. The U.S. Air Force's Advanced Tactical Fighter (ATF) will serve as the primary example of how this integration is currently being pursued, based on experience with both the F-15 and F-16.

INTRODUCTION

"The objective of the fighter pilot is to locate, identify, engage, and kill the opponent...against all odds...under all situations...many times; anything else is absurd."

This paraphrase from a famous World War I fighter ace has been oft repeated throughout the history of aerial combat. While these words may never have constituted a complete doctrine, they can still be found nailed above the bar at more than a few fighter bases. Having weathered the test of time, they profoundly capture an essential definition of the mission.

Since World War I, there has been one major lesson demonstrated: with air superiority, you ensure your ground and other air components can fulfill their missions. Basic aerospace doctrine of the United States Air Force requires that our first consideration in conducting warfare is to establish air superiority. It allows the freedom of action necessary to conduct all other phases of the air/land battle; it spans both strategic and tactical actions, and it gives the tactical flexibility necessary in modern conflict. The bottom line is that it is the prerequisite to winning a war, and the U.S. is not the only country to recognize that fact.

While the fundamental objective has not changed over the years, the tools and tactics with which we accomplish it have certainly come a long way. The evolution of air combat has fallen into cycles of theory and practice, driven by the development and application of new technologies. Historically, as they mature in peacetime, they seem to render the lessons of the past wars obsolete. Following the classic dogfights of the Korean conflict, our new supersonic fighters with radar and air-to-air missiles began to enter service, promising to make us all aces without ever having to engage in visual combat with the enemy. The Vietnam conflict, however, revealed the limitations of this theory and caused us once again to relearn basic lessons in air combat. The Vietnam experience also bred another major technological evolution in more reliable, increased aspect, short-range heat-seeking air-to-air missiles.

Most current fighters, such as the F-15 Eagle and F-16 Falcon, are products of the post-Vietnam cycle, combining the merits of the traditional fighter - good visibility, excellent handling and lethal weapons - with supersonic speed, quick acceleration, and a much expanded maneuver envelope. The F-15, the USAF's current air superiority aircraft, set a completely new standard in fighter capability over the past decade. Translating substantial raw power and low wing loading into outstanding acceleration and maneuverability, the Eagle demonstrates a quantum leap forward in terms of aircraft performance and agility. Incorporating advanced avionics and a powerful long-range radar with look-down/shoot-down capability, the Eagle is able to take advantage of a full complement of medium-range radar-guided Sparrow and short-range heat-seeking Sidewinder air-to-air missiles, along with a high-speed 20mm Gatling gun. The aircraft handling qualities have likewise won the unqualified praise of pilots, representing a major improvement over earlier fighters and allowing them to easily fly anywhere in the flight envelope without fear of going out-of-control. The F-15 Eagle, designed in the late 1960s, is still the best fighter in the world, able to match or out-perform current Soviet fighters including the MIG-29 Fulcrum.

My discussion will examine how advancing technology will continue to help the future fighter pilot meet the threat--and be successful! To limit my remarks, my assessment will concentrate entirely on the air superiority mission. We will look at the tools with which the pilot does his mission, focusing not only on basic improvements in aircraft performance and maneuverability, but more importantly, on greater sophistication in avionics, armament, and the cockpit environment. Enhanced pilot performance, through improvements in the pilot/vehicle interface (PVI) will be a central theme. This major area of interest has focused on improving pilot situational awareness, which will be discussed in detail as we go on. Emerging aerodynamic, propulsion and flight control technologies, coupled with avionics and munitions improvements, will enable us to do the mission more effectively and be successful against more formidable threats. Quantum leaps in performance, thanks to greatly improved thrust-to-weight ratios, provide a whole new dimension to the air battle.

One common denominator still prevails, however; namely the pilot, with his trusty Mark I eyeball and accompanying physiological limitations. Significant improvements in tactical worth (i.e., lethality and survivability) afforded by better flying machines must be conditioned by pilot compatibility (i.e., workload and physiological tolerance). How well we do this in our future fighters will be the major difference between victory or defeat. Recent combat experience has shown that aircraft of the newer generation will convincingly defeat the older types under almost any circumstances, as evidenced by the overwhelming success of the Israelis in the Bekaa Valley and the British in the Falkland Islands. After accounting for differences in basic piloting skills and tactics employed, the ultimate determination of success in aerial combat rests largely with the relative sophistication of the aircraft involved.

THE FUTURE THREAT

In the near future we will be faced with ever more formidable adversaries. Over the last 15 years, the Soviets have made tremendous strides in fighter technology. With the development of the MIG-23 Flogger and SU-24 Fencer in the early 1970s, Soviet fighters featured advancements in avionics and armament over earlier MIG-15, -17, -19 and -21 aircraft. With development of the MIG-31 Foxhound in the late 1970s, the Soviets had definitely demonstrated the ability to build high technology fighters. Today, the Soviets are rapidly introducing the MIG-29 Fulcrum and the SU-27 Flanker. Like Western fighters, they have quicker acceleration, better maneuverability, more sophisticated avionics, and longer endurance than their predecessors.

We project continuing improvements to these aircraft, as well as introduction of even newer aircraft into their inventory by the late 1990s. These aircraft, netted with their version of the AWACS--called Mainstay--will be a definite threat to our ability to conduct air operations. In future conflicts, more aircraft will be able to reach combat in time to take part, and they will be able to sustain combat for a much longer period. The result is that future air battles will likely be large scale, multi-aircraft "furballs". Faced with continued improvements in short-range air-to-air missiles, this becomes a less than optimum or preferred scenario for aerial combat. In any such engagement, the chance that a task-saturated pilot will fall victim to a surprise shot from an unseen attacker is greatly increased. Losing an F-15C to a novice in a MIG-21 is not our idea of an acceptable exchange!

Added to this advanced technology capability is the Soviets' ability to produce shear numbers of aircraft. By the year 2000, almost their entire force will be made up of advanced, look-down/shoot-down fighters. If the United States had the recent Soviet rate of fighter production, we could replace our entire active Air Force fighter inventory every one and a half years. Clearly, the challenge for our future fighters remains with our ability to build in the technology to counter a numerically superior enemy.

FUTURE MISSION REQUIREMENTS

Focusing on the air superiority role, a primary mission of future fighter aircraft will be to conduct offensive counterair missions in enemy airspace as part of the Air Commander's coordinated force package. For our air-to-surface interdiction aircraft such as the F-111 and F-15E to be as effective as possible, it is necessary for air superiority fighters to attack the enemy's high-valued airborne platforms. These include the threat aircraft mentioned earlier: Fulcrums, Flankers, Foxhounds, and Mainstay, and in the not too distant future, even newer versions of Soviet counterair and air superiority fighters. To accomplish this task, the future air superiority fighter must be survivable against the defenses projected in the late 1990s and beyond. Added to the airborne threats will be even more sophisticated surface-to-air missiles (SAMs). The lethal envelopes of future Soviet SAM systems will virtually saturate entire blocks of airspace. Clearly, these threats will require the proper balance of improved supersonic maneuverability/persistence, reduced observables, and an integrated avionics/fire control/electronic countermeasures (ECM) system. Avoiding the "furball" kind of aerial combat and employing "dash in, attack and reposition" tactics will be the order of the day.

The characteristics just described will also lend themselves to improved capability in defensive counterair scenarios. The primary objective in this case is to destroy, neutralize, and disrupt the threat attack force. The improved supersonic performance and quicker acceleration capability will allow the future air superiority fighter to selectively engage and disengage at will, while providing excellent close-in combat capability. These performance improvements, combined with a balanced armament suite of medium and short-range all-aspect missiles and an internal gun, will give the theater commander the necessary defensive counterair aircraft he requires.

THE USAF'S NEXT FIGHTER AIRCRAFT

The USAF's Advanced Tactical Fighter (ATF) program will provide this necessary future capability. First and foremost, the ATF is designed to engage and shoot down large numbers of enemy aircraft, as was the F-15 Eagle. As the follow-on to the F-15, the ATF is being designed from the outset to fight outnumbered, against the best the Soviets can field, and do it in enemy airspace! Clearly, this is a formidable challenge. Emerging technologies and their effective integration across a broader spectrum than in any previous fighter aircraft will enable us to meet this challenge and sustain a dominant margin of superiority.

The characteristics we feel are necessary to counter the future threat are outlined in Figure 1.

Figure 1. KEY CHARACTERISTICS TO COUNTER THREAT

- SUPPORTABILITY - INCREASED R&M/DEPLOYABILITY
- REDUCED OBSERVABLES AND PASSIVE SENSORS
- EFFICIENT SUPERSONIC CRUISE AND MANEUVER
- IMPROVED GROUND SURVIVABILITY
- LONGER COMBAT RADIUS ON INTERNAL FUEL
- AFFORDABILITY

For the first time in a fighter development program, reliability and maintainability (R&M) is a number one goal. The ATF is expected to provide the high wartime sortie generation rate required for sustained combat operations in the European theater. The ATF will incorporate reduced observables and passive sensors that will allow it to operate within hostile airspace with relatively low vulnerability to surface-to-air and air-to-air threats. It will have the ability to sustain supersonic speeds both to and from the air battle and also to engage and disengage as necessary. This presents a unique challenge to the designers - building an airframe that not only incorporates low observable features, but also has the aerodynamic design to sustain supersonic cruise and outmaneuver opponents.

The ATF will feature improved ground survivability through its quick turnaround time, short takeoff and landing (STOL) capability, and shelter compatibility. Another major characteristic is its longer combat radius on internal fuel, accomplished through efficient aerodynamic design and improved performance engines. Finally, a necessary objective of the ATF program is affordability. Using the F-15 program as a guideline, we are striving to make the overall life-cycle cost of the ATF less than that of the F-15. The ultimate goal will be to have enough fighters with sufficient technical advantage over projected Soviet fighters to fight outnumbered - and still win! I will now expand on some of these major characteristics from the pilot's perspective.

ACHIEVING MISSION EFFECTIVENESS

As I mentioned earlier, key to the mission effectiveness of a future fighter such as the ATF will be its ability to achieve first-look/first-kill against multiple targets. This requires the proper integration of advanced technologies in the areas of sensors, armament and cockpit displays. The net effect of this technology is to enlarge our own engagement envelope relative to the enemy's radar and IR-cued threats and bring about radical changes in aerial warfare tactics.

Beyond Visual Range

One example, in the air-to-air regime, is the advent of a true beyond-visual-range (BVR) capability made possible by the evolutionary development of the AIM-120 Advanced Medium Range Air-to-Air Missile (AMRAAM), a more capable and effective missile compared to the earlier AIM-7 Sparrow. The launch and leave capability of AMRAAM does not require constant target illumination, a big tactical advantage over the current semi-active AIM-7 Sparrow missile. This allows the pilot opportunity for multiple simultaneous attacks while maintaining an overview of the target area in a track-while-scan mode of his radar. The increased speed and maneuverability of AMRAAM itself increases the lethal employment envelope and makes possible new tactics to enhance survivability. Coupled with an accurate, long-range target identification (ID) system, true BVR aerial combat will become the preferred tactic.

The ability to capitalize on this evolutionary improvement in operational capability depends to a great extent on improved multimode sensors, both passive and active, which rely heavily on advances in micro-electronics. Very High Speed Integrated Circuit (VHSIC) technology provides the modularity necessary for compact packaging and increased R&M. Some of its uses envisioned in the ATF avionics suite are: an active array radar, an infrared search and track system (IRSTS), an integrated electronic warfare system (INEWS) and integrated comm/nav/ID avionics (ICNIA). Of course, the most important concept involved here is that these systems be optimally integrated to provide the pilot with the situational awareness he requires to locate the enemy, engage and defeat him, and survive.

Pilot Situational Awareness

Our tactical air force's definition of situational awareness is knowledge of the current and near-term disposition of both friendly and enemy forces within a volume of space. It is a pilot's state of mind, formed from information from a number of sources and tempered by his observations and experience.

To enhance situational awareness, we are working very hard on cockpit designs which will present to the pilot key information such as target identification, prioritization, threat information, weapon status, etc. that will allow him to survive and win in a heavily defended battle arena. A typical cockpit arrangement may feature liquid crystal color displays, a holographic head-up display (HUD), and voice/hands-on-throttle-and-stick (V/HOTAS) controls. Consideration has to be given to human physiological limitations under high G operation in a nuclear, biological and chemical (NBC) environment. Various methods to accommodate pilot physiological limitations such as articulating ejection seats and partial pressure suits are under consideration.

This important attention to pilot situational awareness has fostered a whole new area of study called Fighter Battle Management (FBM). The avionics capabilities just mentioned will require a comprehensive integration effort to ensure that the individual pilot, his wingman and other fighter elements will be effective in the large scale, highly dynamic and complex air/land battle environment of the future. The importance of developing effective FBM cannot be overemphasized and will be discussed in detail later on.

Survivability

Once targets are located and identified as threats to the pilot, he must have the capability to shoot them down. The ATF will employ a balance of medium and short-range armament, with sufficient carriage to sustain multi-target engagements. The AMRAAM I mentioned earlier, will give the pilot the added tactical flexiblity necessary to engage multiple targets beyond visual range and achieve a first-look/first-shot advantage. A similar evolutionary development in the short range all-aspect missile, called ASRAAM, will provide the pilot a "point and shoot" capability required in the multi-bogey, close-in maneuvering arena against an all-aspect capable enemy. Because missiles have minimum range and maneuver limitations, an internal gun is an essential part of the weapons complement. Combined with an enhanced all-aspect gunsight, it will provide flexibility and supplement these weapons in the close-in arena. Unique to the ATF will be the requirement to carry its ordnance internally for low drag/low observable considerations.

Clearly, to achieve the kill ratio required against a numerically superior enemy in the high threat environment of the future, increased survivability over current fighters is mandatory. Besides being able to sustain supersonic operations and outmaneuver any enemy aircraft, the cues an adversary would use to his advantage...like your own electronic emissions and IR and radar signatures...will be reduced through low observables technology. Delaying detection by the hostile's sensors increases your own first-look/first-shot advantage. Low probability of interception (LPI) features will be built into the radar to minimize electronic cues to the target, while improved passive electronic surveillance and an infrared search and track system (IRSTS) will reduce reliance on active radar. This in turn degrades the capability of a threat to detect, track, launch, and fuze a weapon against your own emissions.

The same low observable technology will also reduce the ATF's vulnerability to surface-to-air missiles. The increased effectiveness and proliferation of improved surface-to-air missiles (SAMs) over the battle area pose additional threats for future fighters. To counter, low observable technology employed by the ATF will reduce the fighter's radar cross-section (RCS), shrinking the lethal engagement envelope of SAM systems. Supersonic persistence and supersonic maneuver will also reduce exposure to SAMs, allow shorter-range systems to be quickly overflown, and permit evasive action against larger missiles at the limits of their range.

STOL capability will reduce runway dependency, allowing for dispersed operations and the ability to operate off battle damaged runways. To reduce exposure on the ground, we are designing in a quick combat turnaround capability and will be able to operate out of current generation shelters.

Performance Improvements

A major characteristic of the ATF is its increased performance capability over current fighters. What is especially significant will be its non-afterburning performance which represents a quantum improvement. This not only allows the pilot to expand the combat envelope, but also provides him more "staying power" during an engagement. This oftentimes can become a limiting factor in combat and a definite concern to the pilot. Just as increased performance without afterburner affords more combat time, the ability to cruise supersonically without afterburner will greatly increase the ATF's combat radius over current fighter aircraft.

This attribute of increased performance can also be translated into a greater sustained G or turn capability. Thanks to improved thrust-to-weight and reduced drag, the ATF will show a significant improvement over current aircraft. With supersonic sustained turn capability, the ATF will have a higher sustained G turn capability over a much wider portion of the flight envelope than current fighters. This capability will also allow the ATF to outmaneuver his adversary and survive, even in a close-in engagement scenario.

Another improved performance feature of the ATF will be its increased acceleration capability. In an advanced BVR fighter, this allows the pilot to go quickly from detection range to missile firing range and, at the same time, increases the max firing range by imparting extra energy to the missile at launch. Again, the low drag configuration coupled with a high thrust-to-weight ratio will give the ATF a significant acceleration improvement when compared to current fighter aircraft. This becomes very important, either to regain lost energy during a maneuvering engagement or to rapidly disengage. Additionally, the ATF's vectoring engine nozzles will provide enhanced maneuverability in a turning engagement. This provides a tactical advantage, allowing the pilot to rapidly point and shoot at the target, just one more positive aspect to survivability.

Sustainability

As mentioned, one of the primary characteristics for ATF is designed-in improvements for increased R&M. This is the first U.S. fighter aircraft program where specific R&M goals have been established right from the start of design. It is this kind of technology that will enable the ATF to greatly exceed the system performance and reliability levels of current fighters and improve combat capability. Designed-in systems will increase self-sufficiency over any existing fighter, enabling the ATF to be deployed more easily and operate from austere locations.

When it's the winning number of sorties that ultimately counts and we are initially fighting greatly outnumbered, it simply means that we will have to use our own fighters more often. The net effect of increased R&M and self-sufficiency translates to improved readiness and sustainability over current fighter aircraft.

To make the ATF a truly effective fighting machine, we are striving to make the aircraft a totally integrated system. This will be accomplished through fault-tolerant systems and maximum use of multipurpose sensors, displays, and components. Drawing on extensive technology development programs of the past decade, the ATF will integrate fire, flight, and propulsion controls. Advances currently being demonstrated in experimental flight test of active fly-by-wire digital flight control systems, with task-tailored algorithms, will optimize ATF stability and handling characteristics for particular tasks and flight conditions. An integrated electronic warfare system (INEWS) will reinforce the ability to penetrate enemy airspace undetected. Achieving maximum combat capability will require careful integration of advanced sensors, digital data and signal processors, multiplex distribution of their outputs, and increasingly sophisticated software.

FOCUS ON OPERABILITY

While technology is rapidly enhancing hardware capabilities, - the pilot's ability to perform his mission successfully remains the bottom line in determining overall aircraft combat effectiveness. The world's most capable aircraft cannot become the premier combat fighter without ultimately considering the pilot. As already alluded to, perhaps the greatest design challenge for future fighter aircraft will be the pilot/vehicle interface (PVI) considerations. The goal should be to design the pilot into the cockpit, making the aircraft an extension of his capabilities, rather than the other way around. A central design objective of the ATF program is to integrate in optimal fashion all the various systems that individually hold so much promise, and to provide the pilot the maximum ability to use them effectively in combat. With the workload in today's F-15 and F-16, pilots are hard-pressed to fully utilize all of the capabilities available to them...and an ATF will potentially present the fighter pilot with an enormous increase in capabilities.

Pilot Workload

The workload of the fighter pilot has become largely one of problem solving and information processing. The number of cockpit controls and displays has proliferated since World War II to a point where there are more than 300 in the F-15 today. The ATF, in turn, will require a giant step forward in cockpit design to reduce pilot workload. Automation will have to be exploited to the fullest to enhance, not diminish, the pilot's responsibilities and roles. The PVI problem will have to be worked prudently to keep the airplane from out-flying the pilot. The key will be to allow the pilot to focus on the critical aspects of the mission, rather than being overloaded with information he can't handle at a time when he can least afford to lose concentration.

For example, two fighters 100 miles apart and converging at Mach 2 speeds will merge in about 2 minutes. Obviously, this leaves the pilot precious little time to detect, identify, carry out tactics, and employ his weapons while also coordinating with his wingman. Compounding the problem is the multitude of data, available from numerous sensors reaching out to ever-increasing ranges, that compete for the attention of the pilot.

Current-generation fighters tend to inundate the pilot with tremendous amounts of highly compressed data from many sources. In contrast, the ATF pilot will be given processed situation information, when and where he needs it. The goal is to integrate man and machine to an unprecedented extent - pilot, airframe, engines, weapons, fire controls and sensors - all communicating together. In the case of an onboard system problem, for instance, the pilot will be informed and provided recommendations. Options will be presented when the aircraft's sensors call for evasive action or weapons employment decisions. In short, the pilot will know exactly what's going on and what options there are to deal with the situation, with all the information provided rapidly and in easy useable fashion.

Effective integration and automation will allow the fighter pilot to gain tremendous combat leverage with his high performance aircraft in tomorrow's tactical environment. As I've previously mentioned, the primary emphasis in designing the optimum PVI is in enhancing pilot situational awareness. The lack of adequate situational awareness is an unrelenting, pervasive problem. A majority of combat pilots are shot down by aircraft they never see or are aware of.

Tactical air battle management - monitoring the status of threats, other friendly aircraft, terrain, weather, and the tactical situation, to say nothing of our aircraft systems - poses a highly complex problem for the fighter pilot. Added to this are the overwhelming number of aircraft involved, internetted with extensive command and control communications. The future air battle arena promises to be even more complex. Larger numbers of aircraft will play, with more real-time command and control communications interacting in a dense EW environment. The pilot's ability to cope in this increasing complexity of the combat environment is hindered by current fighter avionics designs. What has worked well on a limited scale in the past will no longer be viable in the large, highly dynamic and complex air/land battle environment. Quite simply, the pilot will be "maxed out" with greater demands on his attention and concentration.

FIGHTER BATTLE MANAGEMENT

To deal with this concern, an entire new program has evolved within the USAF Systems Command termed Fighter Battle Management (FBM). The thrust of this program is to (1) significantly improve the pilot's situational awareness, and (2) increase the combat effectiveness of the individual pilot and other friendly aircraft to successfully accomplish their assigned roles in a large scale air/land battle environment.

The scope of the Fighter Battle Management program is to develop and assess advanced technology concepts which could be applied to enhance the cockpit environment of future fighter aircraft in the post-1995 time period. Development of such an ultra-smart battle management system is critical to the overall combat effectiveness of tomorrow's fighter pilot. The program plan defines a structured, iterative process to analyze the requirements, to conduct system design analysis, and to assess designs in a simulated tactical combat environment. Essential elements of the plan consist of:

- A generic process to synthesize, develop, and evaluate Fighter Battle Managment system concepts.
- Development of generic Fighter Battle Management technologies and design criteria/guidelines for application to both new fighter weapon systems and as improvements on existing fighter systems.
- Capability to continually assess a broad range of future Fighter Battle Management technologies and related developments in aircraft, avionics, weapons, crew stations, and command and control.

Aiding Pilot Workload

Effective Fighter Battle Management will consist of onboard sensing and receiving, intelligent processing, decision-aiding, and pilot/vehicle interfaces. It will address three major functional capabilities: information fusion, pilot decision-aiding, and workload management.

(1) Information Fusion. This capability assimilates inputs from a variety of sources and presents what the pilot needs, when he needs it...in an intuitive, easily understood manner. Information from onboard sensors is correlated, filtered, and processed to reduce the vast amount of raw data available into essential, prioritized pictorial displays or other means of stimulus from which the pilot can easily understand the battle situation. This function is intended to greatly relieve the current problem of either "information overload" or lack of the right information at the right time. In today's fighters, it is all too easy to become saturated with data inputs. The tendency is to "filter out" or channelize attention to what the pilot deems important at the moment, sometimes compromising total situational awareness.

(2) Pilot Decision-Aiding. To help overcome the "data overload" problem, a second major functional capability will be pilot decision-aiding. A number of emerging technologies and technology-base programs are becoming available which promise to aid the pilot in coping with data saturation by processing it into useable information. Technology examples include automated identification methods, real-time command and control, artificial intelligence, few-on-many fire control solutions, and pilot/vehicle interface technologies. Decision-aiding will be beneficial to the pilot in establishing threat

intent, target prioritization, weapons launch envelopes, threat lethal zones, flight management algorithms for fire control, terrain following/terrain avoidance/threat avoidance, weapon delivery, and defensive options. Current radar algorithms for the F-15 and F-16 provide first-generation automated capabilities in some of these areas. With incorporation of radar track-while-scan features and the addition of AMRAAM, target prioritization and few-on-many fire control solutions become extremely important.

(3) Workload Management. This capability will dynamically allocate task loading to the pilot, the system, or a combination of man/machine operations. Automation is based upon need and performance capabilities. Design concepts will turn away from subsystems which provide the pilot an unlimited number of options to those which are automated to provide the most appropriate options for a given situation.

The pilot will still remain actively involved in primary decision making and control. Avionic function automation must avoid compromising the pilot's ability to exercise control over the system when necessary. Functional allocation of tasks to either man or machine will be based upon the knowledge of pilot capabilities/limitations and machine capabilities. Mission task time-line analysis is applied to avoid excessive pilot perceptual saturation, simultaneous event/peak task loading, and excessive routine subsystem tasks which distract the pilot's situational awareness. Expendables (fuel, weapons, countermeasures) can be optimally managed automatically to assist the pilot in accomplishing the mission.

Good examples of cockpit workload management are found in the F-18 and the F-15E Dual Role Fighter. Adapting from success with the F-18, the designers have further improved cockpit functional integration in the F-15E two-place long-range interdiction/fighter aircraft. Sensor, flight management, and attack displays are presented on cathode ray tube (CRT) displays for both the pilot and weapon system operator (WSO). Displays are pre-programmed to provide the appropriate information for the phase of the mission underway with minimal switchology. Total flexibility allows either crewmember to take control of sensors and displays or to work them independently, retaining near-simultaneous air-to-air and air-to-ground situational awareness and attack capability.

FBM Building Blocks

Preliminary Fighter Battle Management analytical work is underway at the Aeronautical Systems Division of U.S. Air Force Systems Command at Wright Patterson Air Force Base, Ohio. A structured process is being established to define the requirements and to analyze baseline FBM concepts. One program already underway, Cockpit Automation Technology (CAT), is developing a structured methodology, computer-aided design tools, and performance metrics for systematically designing crew stations. While CAT is predominantly a crew station design methodology, the tools they develop will be applied constructively to Fighter Battle Management design. These designs will be introduced in a highly dynamic environment, employing realistic sets of tactical mission scenarios to fully evaluate technology applications, integration and tradeoffs.

A number of other critically important technology-base programs are currently under development or are programmed which will serve as the building blocks for Fighter Battle Management. These independent programs satisfy various tactical mission needs and consist of:

- Air-to-Air Attack Management and Integrated Control/Avionics for Air Superiority (ICAAS). This program provides solutions for offensive attack of "few-on-many." It includes sensor fusion, sensor internetting between aircraft, missile avoidance/evasion, and pilot/vehicle controls and displays.

- Pilot's Associate. This program emphasizes the application of artificial intelligence to tactical fighters for multi-spectrum missions. It integrates several avoinics functions to assist the pilot with information management, planning, and decision-aiding. The intent is to take the mundane workload off the pilot and free him to conduct essential battle management functions. A pilot's associate expert system would perform numerous monitoring, statusing, and assessment roles and present only the required and relevant information to the pilot.

- Survivable Penetration and Attack. This program develops technology for air-to-surface missions including low level penetration (TF/TA), decision-aiding for options on terrain masking, countermeasures, defense suppression, target acquisition, coordinated attack, and weapon delivery. This effort will rely heavily on a digital terrain management and display system, utilizing three-dimensional digitalized terrain maps stored in the flight management computer.

- Super Cockpit. This program complements the pilot's associate, where a number of advanced cockpit technologies and design methods will be evaluated from which pilot/vehicle interfaces can be selected and refined. A rapidly reconfigurable crew station will be employed to carry out prototyping efforts. The Super Cockpit is seen as the culmination of all the research in recent years on cockpit technologies. Also included will be advanced developments with helmet-mounted displays and voice activated controls. The aim is to help pilots manage their increasingly demanding workloads in an even-tougher combat environment. The Super Cockpit will be the medium for integrating the capabilities of the machine with the intelligence of the human.

Early technology available from the Super Cockpit effort, projected for incorporation into the ATF, will feature an all-aspect head-up display (HUD) and head-aimed fire control. This HUD will project information on the pilot's helmet visor as well as sense motion and orientation of the head. The all-aspect information display offers a definite advantage over the convential HUD mounted on the instrument panel. Being pilot oriented, it will also function better with the possible reclined seating in future fighters. The head-aimed fire control feature will cue preliminary heading information to air-to-air missiles, as well as direct the infrared sensor system. Later versions of Super Cockpit, to be introduced in the 1990s, will offer coupled eye/voice control, virtual imagery, and monitoring of the pilot's physiological state.

The "Big Picture" Cockpit

The dynamic nature of future aerial combat will require that the pilot have a "big picture" of the overall tactical situation as well as detailed targeting and weapon delivery information. In today's fighters, information is provided piecemeal from specific sensors or data sources which drive individual multifunction displays. This forces the pilot to be the integrator, observing all cockpit displays in near-simultaneous fashion and form tactical decisions. In a more dynamic or complicated scenario, this workload rapidly reaches a peak and situational awareness suffers.

The proposed solution for future fighter aircraft is to integrate all available data and provide processed information relevant to a particular situation on a single display. This would potentially clutter current display capabilities (largest 36 square inches), so a much larger display area (300 square inches) is one suggested option. Through the use of software programming flexibility, the electronic head-down display (HDD) could be configured to have one large display, several current size displays, or a combination of both. The HDD would also be touch-sensitive for direct pilot interaction. This key pilot/vehicle interface would be combined with a wide field-of-view holographic HUD, a helmet-mounted display (HMD), a helmet-mounted sight (HMS), an advanced voice interactive system, hands-on-throttle and stick (HOTAS) controls, and a data transfer module (DTM). The net effect of all these PVI features will be to integrate the pilot and aircraft as much as possible, enhance situational awareness, and achieve maximum combat utility.

To evolve and iteratively assess all of these technologies for better operability and effective Fighter Battle Management, engineering simulation is an absolute necessity. Simulation is an integral part of practically every aircraft, integrated avionics, and weapon system development program. No adequate models exist by which analysis alone can faithfully represent a pilot's ability to sense, adapt, reason, and act in complex air battle situations. Simulation is the only design tool, short of flight testing, by which we can measure the impact of design changes upon mission performance, effectiveness, and workload under realistic combat conditions. It provides a true measure of comparison for design tradeoffs and its worth has been proven time and again. For all these reasons, the pilot must be actively involved in carefully controlled high-fidelity, multi-engagement, piloted simulations which accurately present the stress, complexity, and uncertainity of the air battle.

SUMMARY

Having discussed both the threat and mission requirements for future fighter aircraft, it is obvious we are faced with formidable challenges. The key characteristics envisioned for future fighters will rely heavily on successful application and integration of emerging technologies. Fighter Battle Management, with its emphasis on effective systems design and integration for operability and enhanced situational awareness, will provide the pilot the leverage to get the most out of his machine in combat.

In conclusion, I would like to reiterate my opening statement another way: all of the innovative technologies and their application should be focused on just one thing - providing the fighter pilot an aircraft he can fight and win with, at the time and place of his choosing!

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UTTL: Yakovlev Forger
AUTH: A/BRAYBROOK, R. Air International (ISSN 0306-5634), vol. 31, Aug. 1986, p. 81-86.
ABS: Although it appears that the Soviets began development of a VTOL aircraft in the 1960s, the expense of the effort may have delayed the program. The concept of jet lifting was retained and tested in the Yak-38 Freehand, which displayed a high degree of automatic stability control but required a deep inset of the cockpit to maintain balance. The Yak-38 Forger was introduced on antisubmarine carriers in 1971 and was tracked at a speed of Mach 1.05 by radar. Numerous comparisons are made between the design features observed in photographs of the Forger and the Harrier aircraft, noting the incorporation of many positive features in the Forger that have only been proposed for the Harrier. Finally, projections are made of the mission scenarios and capabilities of the aircraft.
86/08/00 87A10575

UTTL: Society of Flight Test Engineers, Annual Symposium, 16th, Seattle, WA, July 29-August 2, 1985, Proceedings Symposium supported by the Boeing Co. Lancaster, CA, Society of Flight Test Engineers, 1985, 292 p. For individual items see A86-47777 to A86-47802.
ABS: The present conference on advancements in flight testing methods encompasses topics in test technology development, noteworthy flight test results, the management of test flight programs, the current status of numerous flight test programs, and the state-of-the-art in data-gathering and test instrumentation systems. Attention is given to flight testing of the Tornado terrain-following radar system in bad weather, of high bypass turbofan engines, and of the ground effect behavior of a powered lift STOL aircraft during landing approach. Also noted are the management of software-intensive systems testing, the merits of customer vs. contractor flight testing, precise control surface position measurements for hysteresis and twist bending, an avionics digital data acquisition system, a portable airborne digital data system, inflight loads in existing transport aircraft, flight simulator testing, and flight flutter testing.
85/00/00 86A47776

UTTL: Flight evaluation of a precision landing task for a powered-lift STOL aircraft
AUTH: A/WATSON, D. M.; B/HARDY, G. H.; C/INNIS, R. C.; D/MARTIN, J. L. PAA: D/(NASA, Ames Research Center, Moffett Field, CA) CORP: National Aeronautics and Space Administration. Ames Research Center, Moffett Field, Calif. IN: Atmospheric Flight Mechanics Conference, Williamsburg, VA, August 18-20, 1986, Technical Papers (A86-47651 23-08). New York, American Institute of Aeronautics and Astronautics, 1986, p. 214-231.
ABS: A flight research experiment was conducted with the NASA-Ames Research Center's Quiet Short-Haul Research Aircraft to determine the factors which influence the touchdown distribution for a powered-lift STOL aircraft. The pilots were given two tasks for each of a series of precision approaches flown using a microwave landing system (MLS) in simulated instrument meteorological conditions. They flew the aircraft, with forward vision obscured by a screen, to a 100-ft decision height using a flightpath-oriented, color electronic display and one of four levels of control augmentation. Approaches were flown along a nominal 6 deg glidepath, as well as to calibrated offsets at the decision height to establish a variety of initial conditions for the landing task. The screen was removed at the decision height and the pilot was briefed to land in a 200 foot touchdown zone of the STOLport with a sink rate less than 5 ft/sec. Statistical performance envelopes and pilot ratings are used to describe the results of this experiment. The data generated are expected to be useful for establishing STOL aircraft operating requirements and STOL MLS approach criteria.
RPT#: AIAA PAPER 86-2130 86/00/00 86A47676

UTTL: Robust fault detection and isolation for a high performance aircraft on STOL approach
AUTH: A/BADGETT, M. E.; B/WALKER, R. A.; C/HAIGES, K. R. PAA: B/(Integrated Systems, Inc., Palo Alto, CA); C/(Northrop Corp., Aircraft Div., Hawthorne, CA) IN: Guidance, Navigation and Control Conference, Williamsburg, VA, August 18-20, 1986, Technical Papers (A86-47401 23-63). New York, American Institute of Aeronautics and Astronautics, 1986, p. 180-189. Research supported by Northrop Corp.
ABS: Fault detection and isolation (FDI) techniques are becoming increasingly important components of robust, highly reconfigurable aircraft. In this paper, the theoretical and practical aspects of robust FDI design and implementation are discussed. Key issues involving error model realization, error model filtering, and error frequency shaping are addressed. The resulting

techniques are utilized in the design of a FDI filter system for a high performance tactical aircraft on STOL approach. The results of simulated system failures show the clear superiority of robust FDI techniques presented here over conventional filtering techniques.
RPT#: AIAA PAPER 86-2031 86/00/00 86A47421

UTTL: Decision aiding for tactical aircraft
AUTH: A/BROADWELL, M.; B/SMITH, J.; C/BARNETTE, J.; D/STAROS, C. PAA: D/(Lockheed-Georgia Co., Advanced Electronics Div., Marietta) IN: Applications of artificial intelligence II; Proceedings of the Meeting, Arlington, VA, April 9-11, 1985 (A86-46706 22-63). Bellingham, WA, Society of Photo-Optical Instrumentation Engineers, 1985, p. 153-160.
ABS: Some of the tasks of the airborne mission/route planner system under development for tactical aircraft require symbolic reasoning on the basis of subjective and incomplete information. Other tasks call for precise and synchronized processing of aircraft control parameters, while others may be of a nature that is intermediate between the two extremes. Attention is given to this system's design and implementation approach, which involves the subdivision of the route planning problem into a hierarchy of reasoning abstractions reflecting the types of reasoning or computation best suited to the various facets of the problem. 85/00/00 86A46715

UTTL: Requirements and recommendations for the development of theoretical codes and experimental facilities in the near future
AUTH: A/COSTES, B. PAA: A/(ONERA, Chatillon-sous-Bagneux, France) (Institut von Karman de Dynamique des Fluides, Cours, Brussels, Belgium, Athens, Greece, and Ankara, Turkey, Feb. 17-28, 1986) ONERA, TP, no. 1986-10, 1986, 16 p.
ABS: The development of computational fluid mechanics (CFM) techniques and facilities and complementary wind-tunnel facilities is projected over the period 1985-2000, summarizing the findings of a number of published reviews and reports. The strength, limitations, and inconsistencies of current CFM programs are surveyed; the need for greater reliability and for more cooperation among research teams and between basic science and industry is stressed; the reasons for continuing and improved wind-tunnel verification of CFM results are outlined; the advantages of current advanced-design wind tunnels (such as ONERA F2, NASA National Transonic Facility, DFVLR cryogenic tunnel, and some adaptive-wall facilities) are considered; and the need for better flow-visualization techniques is indicated. Diagrams, drawings, and graphs of sample data are provided.
RPT#: ONERA, TP NO. 1986-10 86/00/00 86A46155

UTTL: A computer-augmented procedure for commercial aircraft configuration development and optimization
AUTH: A/HABERLAND, C.; B/FENSKE, W.; C/THORBECK, J. PAA: B/(Berlin, Technische Universitaet, West Germany); C/(Deutsche Lufthansa AG, Hamburg, West Germany) (International Council of the Aeronautical Sciences, Congress, 14th, Toulouse, France, September 9-14, 1984, Proceedings. Volume 2, p. 943-953) Journal of Aircraft (ISSN 0021-8669), vol. 23, May 1986, p. 390-397: Previously cited in issue 22, p. 3188, Accession no. A84-45031. 86/05/00 86A40114

UTTL: Computer sizing of fighter aircraft
AUTH: A/COEN, P. G.; B/FOSS, W. E., JR. PAA: B/(NASA, Langley Research Center, Hampton, VA) CORP: National Aeronautics and Space Administration. Langley Research Center, Hampton, Va. (AIAA, Aerospace Sciences Meeting, 23rd, Reno, NV, Jan. 14-17, 1985) Journal of Aircraft (ISSN 0021-8669), vol. 23, May 1986, p. 353, 354. Previously announced in STAR as N85-16759.
ABS: The computer sizing technique has been applied to a number of military mission profiles. Performance data can be determined for all segments of the selected profile, which typically include takeoff, climb, cruise, loiter, reserve and landing segments. Options are available for detailed calculation of combat performance and energy-maneuverability characteristics. Configuration changes, such as external fuel tank drop and weapon expenditure, can be included in the mission. In the sizing mode, aircraft gross weight, wing loading, and thrust-to-weight ratio are varied automatically to determine which combinations meet the design mission radius. The resulting performance data can be used to create a thumbprint plot. This plot is useful in determining the configuration size that best satisfies the mission and performance requirements. The sizing mode can also be used to perform parametric studies such as sensitivity of gross weight to alternate design conditions.
RPT#: AIAA PAPER 85-0212 86/05/00 86A40106

UTTL: Fuel conservative guidance for shipboard landing of powered-lift STOL aircraft
AUTH: A/WARNER, D. N., JR.; B/MCGEE, L. A.; C/MCLEAN, J. D.; D/SCHMIDT, G. K. PAA: B/(NASA, Ames Research Center, Moffett Field, CA); D/(Analytical Mechanics Associates, Inc., Mountain View, CA) CORP: National Aeronautics and Space Administration. Ames Research Center, Moffett Field, Calif.; Analytical Mechanics Associates, Inc., Mountain View, Calif. (Guidance, Navigation and Control Conference, Snowmass, CO, August 19-21, 1985, Technical Papers, p. 307-317) Journal of Guidance, Control, and Dynamics (ISSN 0731-5090), vol. 9, May-June 1986, p. 377-379. Previously cited in issue 22, p. 3225, Accession no. A85-45911. 86/06/00 86A39048

UTTL: ASTROS - An advanced software environment for automated design
AUTH: A/HERENDEEN, D. L.; B/HOESLY, R. L.; C/JOHNSON, E. H.; D/VENKAYYA, V. B. PAA: B/(Universal Analytics, Inc., Playa del Rey, CA); C/(Northrop Corp., Hawthorne, CA); D/(USAF, Wright Aeronautical Laboratories, Wright-Patterson AFB, OH) IN: Structures, Structural Dynamics and Materials Conference, 27th, San Antonio, TX, May 19-21, 1986, Technical Papers. Part 1 (A86-38801 18-39). New York, American Institute of Aeronautics and Astronautics, 1986, p. 59-66.
ABS: The 'ASTROS' Automated Structural Optimization System combines a general purpose executive, a scientific data base management system, and a problem-oriented control language into a powerful and flexible tool for the design of engineering application software. The primary function of such software is the integration of specific functional modules from existing sources into a cohesive system for automated aerospace structure design; this encompasses, in addition to finite element methods, static and dynamic structural characteristics, aerodynamics, sensitivity analysis, optimization, and control systems.
RPT#: AIAA PAPER 86-0856 86/00/00 86A38807

UTTL: The STOL performance of a two-engine, USB powered-lift aircraft with cross-shafted fans
AUTH: A/STEVENS, V. C.; B/WILSON, S. B., III; C/ZOLA, C. A. PAA: B/(NASA, Ames Research Center, Moffett Field, CA); C/(NASA, Lewis Research Center, Cleveland, OH) CORP: National Aeronautics and Space Administration. Ames Research Center, Moffett Field, Calif.; National Aeronautics and Space Administration. Lewis Research Center, Cleveland, Ohio. SAE, Aerospace Technology Conference and Exposition, Long Beach, CA, Oct. 14-17, 1985. 8 p.
ABS: The short takeoff and landing capabilities that characterize the performance of powered-lift aircraft are dependent on engine thrust and are, therefore, severely affected by loss of an engine. This paper shows that the effects of engine loss on the short takeoff and landing performance of powered-lift aircraft can be effectively mitigated by cross-shafting the engine fans in a twin-engine configuration. Engine-out takeoff and landing performances are compared for three powered-lift aircraft configurations: one with four engines, one with two engines, and one with two engines in which the fans are cross-shafted. The results show that the engine-out takeoff and landing performance of the cross-shafted two-engine configuration is significantly better than that of the two-engine configuration without cross-shafting.
RPT#: SAE PAPER 851839 85/10/00 86A38336

UTTL: AV-8B High Angle of Attack/departure resistance system flight test program
AUTH: A/BIGLER, R. A. PAA: A/(McDonnell Aircraft Co., St. Louis, MO) AIAA, AHS, CASI, DGLR, IES, ISA, ITEA, SETP, and SFTE, Flight Testing Conference, 3rd, Las Vegas, NV, Apr. 2-4, 1986. 9 p.
ABS: The AV-8B High Angle of Attack (HAOA) Test Program used a four phase approach to accomplish the goals within the established time constraints. The major goals were evaluating the HAOA flight characteristics as required by military specification and developing stability augmentation software to enhance the aircraft's maneuvering capability. These goals were accomplished during a thirteen month/251 flight program which incorporated Naval Air Test Center participation flights throughout to eliminate extraneous testing and provide the customer with an early appraisal of the HAOA characteristics. The flight test program concluded with a dedicated spin mode and recovery investigation. The test results defined the maneuvering boundary and indicated the aircraft possessed a high resistance to spin dynamics throughout the normal flight regime.
RPT#: AIAA PAPER 86-9729 86/04/00 86A37082

UTTL: Optimization in design processes - An informatics point of view
AUTH: A/VAN DEN DAM, R. F.; B/BOERSTOEL, J. W.; C/DANIELS, H. A. M. PAA: C/(Nationaal Luct- en Ruimtevaart Laboratorium, Amsterdam, Netherlands) International Journal for Numerical Methods in Engineering (ISSN 0029-5981), vol. 22, Feb. 1986, p. 433-450.

ABS: The purpose of this paper is to outline the optimization-system development at NLR. The paper starts with a discussion of the potential of mathematical optimization techniques in aeronautical engineering. Subsequently, the main requirements to be met by a general-purpose optimization system are given. Following this, the implementation at NLR is described, and some examples of applications are presented to illustrate the optimization capabilities. 86/02/00 86A36208

UTTL: Computer-aided cockpit workload analysis for all weather, multirole tactical aircraft

AUTH: A/ROBERTS, B. B.; B/CRITES, C. D. PAA: A/(Computer Sciences Corp., Edwards AFB, CA); B/(USAF, Flight Test Center, Edwards AFB, CA) IN: Aerospace Behavioral Engineering Technology Conference, 4th, Long Beach, CA, October 14-17, 1985, Proceedings (A86-35426 15-54). Warrendale, PA, Society of Automotive Engineers, Inc., 1985, p. 111-123.

ABS: The development of computer-aided cockpit workload analysis that predicts man/machine interface problems is discussed. The logic flow for the Timebased Analysis of Significant Coordinated Operations (TASCO) model is described. The components and procedures of the crew station task analysis and busy rate index analysis performed by the TASCO model are examined. Computer-aided testing is applied to the TASCO model to establish pass/fail criteria associated with operator task performance profficiency.

RPT#: SAE PAPER 851876 85/00/00 86A35439

UTTL: Structural optimisation programs and methods

AUTH: A/MORRIS, A. J. PAA: A/(Cranfield Institute of Technology, England) IN: International Symposium on Aeroelasticity and Structural Dynamics, 2nd, Aachen, West Germany, April 1-3, 1985, Collected Papers (A86-33226 14-01). Bonn, Deutsche Gesellschaft fuer Luft- und Raumfahrt, 1985, p. 393-406.

ABS: Attention is given to current practices in the CAD generation of minimum weight structure designs. The definition of design variables essentially fixes the form of the objective function; the remainder of the design problem is defined by the constraints limiting the range of values to be taken by the design variables in order to describe a realistic and safe structure. In the case of aircraft, loads are complex and give rise to a nonconservative system, due to the transmission of forces to the structure as a function of the deformed position and the structural/aerodynamic damping. 85/00/00 86A33257

UTTL: An improvement to the numerical method for calculations of aircraft configuration longitudinal aerodynamic characteristics

AUTH: A/JIANG, Z. PAA: A/(China Aerodynamic Research and Development Center, People's Republic of China) Acta Aerodynamica Sinica (ISSN 0258-1825), vol. 4, March 1986, p. 56-64. In Chinese, with abstract in English.

ABS: Based on the subsonic and supersonic potential theory, an improved numerical method is developed for the calculation of the surface pressure distribution on an aircraft and then the force and moment by integrating the pressure distributions, using surface distribution finite element solutions. With concepts of joint flow field and the effective section thrust and strip turbulent boundary layer theory, an improved drag calculation can be obtained. A computer program has been developed. Several examples of calculated aerodynamic characteristics are presented, and good agreement between calculation results and experimental data can be achieved. 86/03/00 86A32994

UTTL: High technology test bed program

AUTH: A/PAYNE, C. B. PAA: A/(Lockheed-Georgia Co., Marietta) AIAA, AHS, CASI, DGLR, IES, ISA, ITEA, SETP, and SFTE, Flight Testing Conference, 3rd, Las Vegas, NV, Apr. 2-4, 1986. 10 p.

ABS: The High Technology Test Bed (HTTB) program, initiated in 1984, is concerned with the addition of performance-enhancing design features to a Hercules test aircraft which facilitate Short Takeoff and Landing (STOL) capabilities and generally enhance tactical cargo mission survivability. Advanced electronics, avionics and cockpit designs are incorporated. Attention is given to the 'tactical assault mission' threat scenario which furnishes the context for HTTB design requirements. The new cockpit incorporates a cockpit management system, a HUD, programmable displays, and an autothrottle. A 'Special Avionics Mission Strap-On Now' pod is used to enhance mission adaptability.

RPT#: AIAA PAPER 86-9803 86/04/00 86A32132

UTTL: Flying qualities design criteria for highly augmented systems

AUTH: A/MOORHOUSE, D. J.; B/MORAN, W. A. PAA: A/(USAF, Wright Aeronautical Laboratories, Wright-Patterson AFB, OH); B/(McDonnell Aircraft Co., St. Louis, MO) IN: NAECON 1985; Proceedings of the National Aerospace and Electronics Conference, Dayton, OH, May 20-24, 1985. Volume 2 (A86-28326 12-04). New York, Institute of Electrical and Electronics Engineers, 1985, p. 1536-1545.

ABS: Interpretation and application of the military flying qualities specification, MIL-F-8785C, as the best guide to excellent flying qualities, is suggested. A summary is given of the government's flight control requirements of the Statement of Work of the STOL and Maneuver Technology Demonstration Program (SMTDP). The program contractor, McDonnell Aircraft Company, has had recent experience developing the digital flight control system of the F/A-18A. Lessons learned from that development are used to define the appropriate interpretations of specific requirements in MIL-F-8785C. These are expressed as preliminary detailed flying qualities criteria for the SMTDP, plus 'second tier' criteria to be used for additional design guidance. 85/00/00 86A28509

UTTL: An integrated flight control system for a STOL transport aircraft
AUTH: A/BRIGGS, P.; B/GARDNER, L.; C/WOOD, T. G. PAA: B/(Sperry Corp., New York); C/(Lockheed-Georgia Co., Marietta) IN: NAECON 1985; Proceedings of the National Aerospace and Electronics Conference, Dayton, OH, May 20-24, 1985. Volume 1 (A86-28326 12-04). New York, Institute of Electrical and Electronics Engineers, 1985, p. 482-489.
ABS: The development of a flight control system (FCS) for short takeoff and landing (STOL) aircraft using the High Technology Test Bed is studied. The main requirements for the future FCS are: (1) autonomous STOL capability, (2) automatic flight path control, (3) control reconfiguration, and (4) a ground-based maintenance diagnostics system; advances in these areas are discussed. The control of the spoilers and tail surface by the DFCS utilizing fail-operational roll stability and control augmentation, direct lift control, fail-operational yaw and pitch stability and control augmentation, and five dual electromechanical actuation systems is described. The input signal management, actuator signal management, synchronization, error handling, power-up reset and recovery, and the built-in test capabilities of the redundancy management of the DFCS are examined. The functional organization of the DFCS is explained. 85/00/00 86A28384

UTTL: CAD/CAM designer - Jack of all trades
AUTH: A/HERNDON, C. F.; B/GALLO, R. L. PAA: B/(General Dynamics Corp., Fort Worth, TX) Aerospace America (ISSN 0740-722X), vol. 24, Jan. 1986, p. 52-54, 56.
ABS: Aerospace design engineers are increasingly required to have more extensive knowledge of CAD/CAM tooling and manufacturing methods, in order to ensure that datasets can yield error-free components and assemblies. For structural concept design, engineers will work at the same CAD/CAM workstation on which the final component will be defined, controlling methods that yield the optimum solution for each member of a structural system from the viewpoints of both weight (for given strength) and producibility. 86/01/00 86A21895

UTTL: Definition and verification of a complex aircraft for aerodynamic calculations
AUTH: A/EDWARDS, T. A. PAA: A/(NASA, Ames Research Center, Moffett Field, CA) CORP: National Aeronautics and Space Administration. Ames Research Center, Moffett Field, Calif. AIAA, Aerospace Sciences Meeting, 24th, Reno, NV, Jan. 6-9, 1986. 9 p.
ABS: Techniques are reviewed which are of value in CAD/CAM CFD studies of the geometries of new fighter aircraft. In order to refine the computations of the flows to take advantage of the computing power available from supercomputers, it is often necessary to interpolate the geometry of the mesh selected for the numerical analysis of the aircraft shape. Interpolating the geometry permits a higher level of detail in calculations of the flow past specific regions of a design. A microprocessor-based mathematics engine is described for fast image manipulation and rotation to verify that the interpolated geometry will correspond to the design geometry in order to ensure that the flow calculations will remain valid through the interpolation. Applications of the image manipulation system to verify geometrical representations with wire-frame and shaded-surface images are described.
RPT#: AIAA PAPER 86-0431 86/01/00 86A19873

UTTL: Computer tools and techniques for analysis of discrete data from aircrew automated escape systems (AAES)
AUTH: A/FRITSVOLD, J. D.; B/VETTER, J. E. PAA: B/(U.S. Navy, Analytical Systems Div., Washington, DC) IN: SAFE Association, Annual Symposium, 22nd, Las Vegas, NV, December 9-13, 1984, Proceedings (A86-19301 07-03). Van Nuys, CA, SAFE Association, 1985, p. 37-40.
ABS: Analyses have been conducted for automated aircrew escape systems, using statistical models generated in part by computer tools to study the significant factors that contribute to problems during ejections or emergency escapes. Extensive use is made in this work of discrete variables that are presented in a frequency table of cross classifications. Significant associations are thereby established, while spurious

ones are rejected. The computational capability in question allows the study of the effects of several factors simultaneously on a variable of interest, such as the likelihood of a severe injury or fatality during an aviation emergency. 85/00/00 86A19302

UTTL: Characteristics of the design of VTOL jet aircraft
AUTH: A/VOLODIN, V. V.; B/LISEITSEV, N. K.; C/MAKSIMOVICH, V. Z. Moscow, Izdatel'stvo Mashinostroenie, 1985, 224 p. In Russian.
ABS: The problems encountered at various stages of the design of VTOL jet aircraft are examined. In particular, attention is given to the calculation of forces and moments acting on VTOL aircraft during vertical takeoff and landing; modeling and analysis of aircraft control during vertical takeoff and landing; functional requirements for the control systems of VTOL aircraft and their design; and the design of the airframe and power plants of VTOL jet aircraft. The discussion also covers the calculations of the weight characteristics of VTOL aircraft, computer-aided design of general VTOL aircraft configurations, and an assessment of the efficiency of VTOL jet aircraft. 85/00/00 86A17600

UTTL: Productivity improvements through the use of CAD/CAM
AUTH: A/WEHRMAN, M. D. PAA: A/(Boeing Commercial Airplane Co., Seattle, WA) (International Council of the Aeronautical Sciences, Congress, 14th, Toulouse, France, September 9-14, 1984, Proceedings. Volume 2, p. 1079-1084) Journal of Aircraft (ISSN 0021-8669), vol. 22, Nov. 1985, p. 1013-1017. Previously cited in issue 22, p. 3222, Accession no. A84-45048. 85/11/00 86A14538

UTTL: Aerodynamics - The role of the computer
AUTH: A/HANCOCK, G. J. PAA: A/(Queen Mary College, London, England) Aeronautical Journal (ISSN 0001-9240), vol. 89, Aug.-Sept. 1985, p. 269-279.
ABS: The use of computers in aerospace aerodynamics is reviewed. Computational aerodynamics has advanced due to increasing computer speeds, growth in memory capabilities, and architectural improvements. Numerical modelling of physical flows, algorithm development, research and production code development, and evaluation and validation of the codes using computational aerodynamics are described and examples are provided. The application of computational aerodynamics in aerodynamic design is discussed. In experimental aerodynamics computers are useful in rig automation, data acquistion and synthesis, the design of test facilities, and the specification of test procedures. The interaction between control systems and aerodynamics is studied. The extraction of aerodynamic information from flight tests with computers is discussed. 85/09/00 86A13050

UTTL: Computational grid generation for realistic aircraft configurations
AUTH: A/SOMMERFIELD, D. M.; B/DULIKRAVICH, G. S.; C/KENNON, S. R. PAA: C/(Texas, University, Austin) AIAA, Applied Aerodynamics Conference, 3rd, Colorado Springs, CO, Oct. 14-16, 1985. 8 p.
ABS: A computational technique is presented for transforming three-dimensional space into a series of two-dimensional planes for conformal mapping of flowfields around aircraft designs. The aircraft geometry is radially sheared to convert the fuselage into a circular cylinder. The lifting surfaces are thereby also radially sheared and stretched. The intersections between the computational surfaces and the distorted lifting surfaces are obtained by fitting spanwise cubic splines to chordwise locations using Newton's iteration scheme. The surfaces are unwrapped after the intersections are determined, yielding planar strips. Further computations identify the grid points for the planes, which can then be rewrapped around the physical space of interest. Sample results are provided for grids generated for the F-16 and NASA F-8 oblique wing aircraft.
RPT#: AIAA PAPER 85-4089 85/10/00 86A11049

UTTL: Aerodynamics perspective of supermaneuverability
AUTH: A/GALLAWAY, C. R.; B/OSBORN, R. F. PAA: B/(USAF, Wright Aeronautical Laboratories, Wright-Patterson AFB, OH) AIAA, Applied Aerodynamics Conference, 3rd, Colorado Springs, CO, Oct. 14-16, 1985. 10 p.
ABS: Technology advances necessary for providing supermaneuverability for new fighter aircraft are discussed. The goal is to perform maneuvers with controlled sideslip at angles of attack exceeding maximum lift, i.e., post stall maneuverability. Another way to achieve the same capability is to increase the maximum lift. Advances in aerodynamics, flight controls, propulsion, fire control systems, air-to-air weapons and visual range combat tactics will all be needed to attain the desired maneuverability and exploit it. Design goals must focus on suppressing high angle of attack instabilities, with the testing of the design concepts to be performed on high fidelity simulators.

RPT#: AIAA PAPER 85-4068 85/10/00 86A11034

UTTL: Integrated Flight Data Processing System - Support for the discipline engineer

AUTH: A/DAVINO, R. M.; B/FLATTERY, D. A. PAA: B/(USAF, Flight Test Center, Edwards AFB, CA) AIAA, AHS, and ASEE, Aircraft Design Systems and Operations Meeting, Colorado Springs, CO, Oct. 14-16, 1985. 12 p.

ABS: The development of an Integrated Flight Data Processing System (IFDAPS) for real time acquisition, display, and processing of aircraft flight test data is discussed. The functions of the IFDAPS hardware components, which consist of super minicomputers and telemetry preprocessing modules in a distributed network, are described. An explanation of the interrelated computer programs in the software system, which are run file generator, acquisition display subsystem, the range control subsystem, and the control storage subsystem, is provided. The benefits of improved flight testing procedures are examined. The use of IFDAPS to evaluate aircraft performance, propulsion, stability and control, and flutter is discussed. The means by which IFDAPS architecture supports the operation through the normal preflight, real time, and postflight phases of aircraft flight testing are described. The programming of the data display formats and processing capabilities to meet specific flight testing requirements is explained. The procedures for data acquisition, display, and analysis are examined.

RPT#: AIAA PAPER 85-4042 85/10/00 86A10970

UTTL: A computer-assisted process for supersonic aircraft conceptual design

AUTH: A/JOHNSON, V. S. PAA: A/(NASA, Langley Research Center, Hampton, VA) CORP: National Aeronautics and Space Administration. Langley Research Center, Hampton, Va. AIAA, AHS, and ASEE, Aircraft Design Systems and Operations Meeting, Colorado Springs, CO, Oct. 14-16, 1985. 12 p.

ABS: Design methodology was developed and existing major computer codes were selected to carry out the conceptual design of supersonic aircraft. A computer-assisted design process resulted from linking the codes together in a logical manner to implement the design methodology. The process does not perform the conceptual design of a supersonic aircraft but it does provide the designer with increased flexibility, especially in geometry generation and manipulation. Use of the computer-assisted process for the conceptual design of an advanced technology Mach 3.5 interceptor showed the principal benefit of the process to be the ability to use a computerized geometry generator and then directly convert the geometry between formats used in the geometry code and the aerodynamics codes. Results from the interceptor study showed that a Mach 3.5 standoff interceptor with a 1000 nautical-mile mission radius and a payload of eight Phoenix missiles appears to be feasible with the advanced technologies considered. A sensitivity study showed that technologies affecting the empty weight and propulsion system would be critical in the final configuration characteristics with aerodynamics having a lesser effect for small perturbations around the baseline.

RPT#: AIAA PAPER 85-4027 85/10/00 86A10958

UTTL: A rapid evaluation approach for configuration development of new aircraft

AUTH: A/PHOA, Y. T.; B/CAMPISANO, F.; C/CHEN, P.-C.; D/WAKAYAMA, G. PAA: D/(Northrop Corp., Aircraft Div., Hawthorne, CA) AIAA, AHS, and ASEE, Aircraft Design Systems and Operations Meeting, Colorado Springs, CO, Oct. 14-16, 1985. 9 p.

ABS: Procedures followed in a computerized rapid evaluation (REV) approach to in-depth evaluations of new aircraft configurations at the early conceptual design stage are outlined. REV permits the incorporation of state of the art technology, design trade-off studies and structural design practices which lead to an optimal planform before metal cutting begins. Details of aerodynamic and structural optimization of a wing are reviewed, including the optimization codes employed in the REV CAD studies. Future extensions of the REV process to aeroelastic tailoring of entire aircraft are discussed from the point of view of the required algorithms, particularly in applications with forward swept wing aircraft.

RPT#: AIAA PAPER 85-3068 85/10/00 86A10932

UTTL: Integrated flight/propulsion control - Methodology, design, and evaluation

AUTH: A/SMITH, K. L.; B/KERR, W. B.; C/HARTMANN, G. L.; D/SKIRA, C. PAA: A/(General Dynamics Corp., Fort Worth, TX); B/(United Technologies Corp., Pratt and Whitney Aircraft Div., West Palm Beach, FL); C/(Honeywell, Inc., Minneapolis, MN); D/(USAF, Aero Propulsion Laboratory, Wright-Patterson AFB, OH) AIAA, AHS, and ASEE, Aircraft Design Systems and Operations Meeting, Colorado Springs, CO, Oct. 14-16, 1985. 24 p.

ABS: Details of the activities performed during each of four phases of the U.S.A.F. Design Methods for Integrated Control Systems program which produced a set of integrated flight/propulsion control laws are summarized. Phase I produced the integrated control system design requirements for STOL, terrain following/threat avoidance/obstacle avoidance, air-to-air combat maneuvering, air-to-surface combat maneuvering, and supersonic cruise. Phase II work yielded a nonlinear simulation model for steady-state and dynamic characteristics of the aircraft, inlet, engine and nozzle, using a modified F-16XL as the testbed. The design and development of the control logic for each mission segment were accomplished in Phase IV, with the logic being evaluated with the Phase III simulation model.

RPT#: AIAA PAPER 85-3048 85/10/00 86A10927

UTTL: Flight testing of avionic systems on the ground

AUTH: A/UNG, M.; B/UNDERWOOD, J., JR. PAA: A/(Southern California, University, Los Angeles); B/(USAF, Edwards AFB, CA) IN: Aerospace simulation; Proceedings of the Conference, San Diego, CA, February 2-4, 1984 (A85-49001 24-09). La Jolla, CA, Society for Computer Simulation, 1984, p. 3-12.

ABS: The Integration Facility for Avionic Systems Testing (IFAST) allows prospective U.S. Air Force avionics systems to be debugged in the course of ground-simulated flights prior to actual flight testing. IFAST uncovers problems with a given system through playback computer analysis of mission data from tapes that were recorded during simulated missions. Attention is given to IFAST's physical plant, the time-shared computer complex configuration and communications systems, and the modes of mission analysis operation. 84/00/00 85A49002

UTTL: Modernization in aerospace

AUTH: A/ROGERS, H. F. PAA: A/(General Dynamics Corp., Fort Worth, TX) IN: White-collar productivity and quality issues; Proceedings of the Symposium on Productivity and Quality: Strategies for Improving Operations in Government and Industry, Washington, DC, September 25, 26, 1984 (A85-43176 20-81). New York, AIAA, 1985, p. 91-94.

ABS: The implementation of technological innovations to increase productivity in the development and manufacture of aircraft is discussed using examples from the F-16 program. It is pointed out that the number of man-hours required to produce an F-16 has decreased from 110,000 in 1979 to less than 30,000 in 1983, with a concomitant increase in the proportion of defect-free aircraft (from 39 to over 50 percent) and substantial savings for both manufacturer and DOD. Specific measures examined include involvement of subcontractors in the technology-modernization program initiated by the Air Force, introduction of the electrical-harness data system, implementation of robotics, office automation, increased use of CAD/CAM, improved computer communications between engineering departments and factory floor, and installation of material-requirements and manufacturing-resource planning programs. 85/00/00 85A43190

UTTL: Application of computer-aided structural optimization in the design of aircraft components

AUTH: A/WELLEN, H. PAA: A/(Messerschmitt-Boelkow-Blohm GmbH, Bremen, West Germany) DGLR, Fachausschussitzung ueber Festigkeit und Bauweisen, Neubiberg, West Germany, May 7, 1984, Paper. 7 p. In German.

ABS: In the aerospace industry, the minimization of the structural weight is one of the vital requirements for an economic design of flight vehicles. A computer-aided structural optimization procedure can provide possibilities for performing a weight-optimal dimensioning of structural members in an automatized form, taking into account the employment of programmed, mathematical methods. It is possible to achieve the weight optimum under conditions involving time and cost advantages in comparison to the conventional design process. The Royal Aircraft Establishment (RAE) in England has developed the Structural Analysis and Redesign System (Stars) for a computer-aided structural optimization. Stars makes it possible to solve the involved mathematical problem with the aid of various optimization methods. A description is presented of the modular design of Stars and its operation. The practical application of Stars is discussed, taking into account the solution of design problems related to the Airbus A 310. Attention is given to calculations based on a simplified finite-element model.

RPT#: MBB-UT-21-84-OE 84/05/00 85A42685

UTTL: The employment of 3-D programs in aircraft design

AUTH: A/ROSS, H. PAA: A/(Messerschmitt-Boelkow-Blohm GmbH, Munich, West Germany) Deutsche Gesellschaft fuer Luft- und Raumfahrt, Jahrestagung, Hamburg, West Germany, Oct. 1-3, 1984. 33 p. In German.

ABS: Since the mid-1960s, aircraft firms have used computer-aided design (CAD) programs for the creation and/or variation of parametric drafts. The development of the required CAD programs requires a logical connection of essential subprograms describing the design. The values of the technical parameters are varied on the basis of a fundamental configuration. This configuration is in most cases established outside the program. The present investigation is concerned with programs which can be employed as a 'mathematical tool' for the design process. The programs are used for the mathematical definition of surfaces and bodies, taking into account also kinematic problems. The considered programs permit three-dimensional design and representation. For this reason, they are generally designated as 'three-dimensional programs' (3-D). A description of the design process is given to provide a basis for the derivation of the requirements which a 3-D program will have to satisfy. Attention is given to currently available programs, and the utilization of 3-D programs in a German aerospace company.

RPT#: DGLR PAPER 84-113 MBB-LKE-11/S/PUB/146 84/10/00 85A40329

UTTL: Aircraft control systems - A projection to the year 2000

AUTH: A/FRASER, D. C. PAA: A/(Charles Stark Draper Laboratory, Inc., Cambridge, MA) IEEE Control Systems Magazine (ISSN 0272-1708), vol. 5, Feb. 1985, p. 11-13.

ABS: Advances in aircraft control systems technology expected to take place by the year 2000 are outlined. An emphasis is placed on the role of integrated aerodynamic, structural, and propulsion systems controls, as well as information systems, mainly in the context of military aircraft application. Consideration is also given to the ultrafault-tolerant and reliable systems and fly-by-wire control systems with integrated redundant sensor subsystems with embedded fault reconfiguration. Finally, pilot/vehicle interface is examined with respect to the systems, design, simulation, and real-time scheduling capability. 85/02/00 85A29125

UTTL: Predicted performance benefits of an adaptive digital engine control system on an F-15 airplane

AUTH: A/BURCHAM, F. W., JR.; B/MYERS, L. P.; C/RAY, R. J. PAA: C/(NASA, Ames Research Center, Flight Research Facility, Edwards, CA) CORP: National Aeronautics and Space Administration. Ames Research Center, Moffett Field, Calif. American Institute of Aeronautics and Astronautics, Aerospace Sciences Meeting, 23rd, Reno, NV, Jan. 14-17, 1985. 9 p.

ABS: The highly integrated digital electronic control (HIDEC) program will demonstrate and evaluate the improvements in performance and mission effectiveness that result from integrating engine-airframe control systems. Currently this is accomplished on the NASA Ames Research Center's F-15 airplane. The two control modes used to implement the systems are an integrated flightpath management mode and an integrated adaptive engine control system (ADECS) mode. The ADECS mode is a highly integrated mode in which the airplane flight conditions, the resulting inlet distortion, and the available engine stall margin are continually computed. The excess stall margin is traded for thrust. The predicted increase in engine performance due to the ADECS mode is presented in this report.

RPT#: AIAA PAPER 85-0255 85/01/00 85A19801

UTTL: Model reduction of control systems

AUTH: A/PUJARA, L. R. PAA: A/(Wright State University, Dayton, OH) Journal of Guidance, Control, and Dynamics (ISSN 0731-5090), vol. 8, Jan.-Feb. 1984, p. 152-155. USAF-supported research.

ABS: It is pointed out that the analysis and design of large-order control systems is quite tedious and costly. For this reason, it is desirable to replace a given large-order system with a lower-order system in such a way that the lower-order system retains the significant characteristics of the given system. The present investigation is concerned with a computer-aided method of simplifying single-variable control systems. The considered method represents a modification of the technique of Rao and Lamba (1974) which can be applied directly to control systems with either a pole or a zero at the origin. The proposed method is a one-step procedure and provides significant savings in computer time in comparison to cases involving the use of the McFIT model reduction technique.

RPT#: AFWAL-TM-83-183-FIGC 85/02/00 85A18350

UTTL: The average $100,000,000 design engineer

AUTH: A/RODENBERGER, C. A.; B/HERNDON, C. F.; C/MAJORS, S. O.; D/ROGERS, W. A. PAA: D/(General Dynamics Corp., Fort Worth, TX) IN: Computers in engineering 1983; Proceedings of the International Conference and Exhibit, Chicago, IL, August 7-11, 1983. Volume 1 (A85-11659 02-31). New York, American Society of Mechanical Engineers, 1983, p. 33-38.

ABS: The value of decisions made by the structural design engineer in designing a modern fighter is estimated over a billion dollars for a production run of 2500 aircraft. In the light of an analysis of the value of design decisions in the aerospace industry, it is shown that 100,000 dollars invested in computer aided design (CAD) support for the structural engineer can result in millions of dollars of savings for each percent improvement. It is emphasized that a particularly large increase in engineering productivity is achieved by integrating computer analyses with CAD systems. 83/00/00 85A11660

UTTL: Analytical design and assurance of digital flight control system structure
AUTH: A/MULCARE, D. B.; B/NESS, W. G.; C/DAVIS, R.M. PAA: C/(Lockheed-Georgia Co., Marietta, GA) (American Institute of Aeronautics and Astronautics, Guidance and Control Conference, San Diego, CA, Aug. 9-11, 1982, AIAA Paper 82-1626) Journal of Guidance, Control and Dynamics (ISSN 0731-5090), vol. 7, May-June 1984, p. 329-337.
ABS: Previously cited in issue 20, p. 3155, Accession no. A82-40434 84/06/00 84A32711

UTTL: Simulation and optimization techniques in computer aided design
AUTH: A/VANDENDAM, R. F. CORP: National Aerospace Lab., Amsterdam (Netherlands). CSS: (Informatics Div.)
ABS: The place and the potential of numerical simulation and optimization techniques in engineering design processes, as well as their use by the designer are discussed. The principles underlying these techniques are outlined and the various methods are reviewed. Examples of applications are presented in order to illustrate their usefulnes in design processes. Attention was paid to the integration of these techniques into structured systems for computer aided design, and to the implementation of these systems in the organization infrastructure.
RPT#: NLR-MP-85022-U B8665120 ETN-86-97670 85/02/22 86N33053

UTTL: Elliptic generation of composite three-dimensional grids about realistic aircraft
AUTH: A/SORENSON, R. L. CORP: National Aeronautics and Space Administration. Ames Research Center, Moffett Field, Calif.
ABS: An elliptic method for generating composite grids about realistic aircraft is presented. A body-conforming grid is first generated about the entire aircraft by the solution of Poisson's differential equation. This grid has relatively coarse spacing, and it covers the entire physical domain. At boundary surfaces, cell size is controlled and cell skewness is nearly eliminated by inhomogeneous terms, which are found automatically by the program. Certain regions of the grid in which high gradients are expected, and which map into rectangular solids in the computational domain, are then designated for zonal refinement. Spacing in the zonal grids is reduced by adding points with a simple, algebraic scheme. Details of the grid generation method are presented along with results of the present application, a wing-body configuration based on the F-16 fighter aircraft.
RPT#: NASA-TM-88240 A-86165 NAS 1.15:88240 86/03/00 86N31527

UTTL: Multi-input, multi-output system control for experimental aircraft
AUTH: A/SCHMIDT, D. K.; B/DUKE, E. L. CORP: Purdue Univ., West Lafayette, Ind. CSS: (School of Aeronautics and Astronautics.)
ABS: Two techniques, direct eigenspace assignment (DEA) and explicit model following (EMF), are used initially to synthesize control laws for the longitudinal dynamics model of a Short Takeoff and Landing (STOL) vehicle in the landing configuration. The vehicle model and the flight control design are presented. The two synthesis techniques are briefly discussed and the handling qualities specifications mapped into the algorithm formulations. The control laws resulting from exercising the algorithms are evaluated in terms of achieved performance and robustness. Since the synthesized control laws involve full state feedback, methodologies were implemented for the control laws using output feedback without adversely affecting performance and robustness. Finally, the salient features of the two design techniques are summarized and the areas that require further investigation are suggested.
RPT#: NASA-CR-177017 NAS 1.26:177017 85/12/13 86N28955

UTTL: The use of mathematical optimization techniques by the designer
AUTH: A/VANDENDAM, R. F. CORP: National Aerospace Lab., Amsterdam (Netherlands). CSS: (Informatics Div.) Presented at Congress on Computer Applications in Production and Engineering (CAPE) Nederland '85, Amsterdam, Netherlands, May 1985
ABS: Mathematical optimization techniques in the design process and their use by designers are discussed. The principles underlying these techniques and the requirements for a flexible optimization system having a broad applicability are considered. Optimization techniques used in aeronautical engineering are reviewed and illustrated with the examples of the System for the Analysis and Constrainted Minimization of Induced Drag and Computational Aerodynamic Design-by-Optimization System.
RPT#: NLR-MP-85005-U B8578430 ETN-86-96975 AD-B098564L

85/01/25 86N28673

UTTL: Geometry definition and grid generation for a complete fighter aircraft
AUTH: A/EDWARDS, T. A. CORP: National Aeronautics and Space Administration. Ames Research Center, Moffett Field, Calif. Presented at the AGARD Symposium on Applications of CED in Aeronautics, Aix en Provence, France, 7-10 Apr. 1986
ABS: Recent advances in computing power and numerical solution procedures have enabled computational fluid dynamicists to attempt increasingly difficult problems. In particular, efforts are focusing on computations of complex three-dimensional flow fields about realistic aerodynamic bodies. To perform such computations, a very accurate and detailed description of the surface geometry must be provided, and a three-dimensional grid must be generated in the space around the body. The geometry must be supplied in a format compatible with the grid generation requirements, and must be verified to be free of inconsistencies. This paper presents a procedure for performing the geometry definition of a fighter aircraft that makes use of a commercial computer-aided design/computer-aided manufacturing system. Furthermore, visual representations of the geometry are generated using a computer graphics system for verification of the body definition. Finally, the three-dimensional grids for fighter-like aircraft are generated by means of an efficient new parabolic grid generation method. This method exhibits good control of grid quality.
RPT#: NASA-TM-88242 A-86208 NAS 1.15:88242 86/04/00 86N28050

UTTL: Man-machine problems in development and operation of computer-aided design systems
AUTH: A/IRUGOV, B. S.; B/PARADIZOV, N. V. CORP: Joint Publications Research Service, Arlington, Va.
ABS: Human factors engineering of computer aided design systems consists in ascertaining and classifying the man machine interactions, efficiently distributing the functions among the machine and human components, and coordinating their joint operations. The ergonomic aspects of the construction of a computer aided design system for printed circuit boards are discussed. The operations performed by human operators are ranked according to the importance of the work station components in terms of the volume of information handled, the duration of each operation, and the influence of fatigue (visual, aural, physical, and psychological) on the operator. A typical illustration (consisting of a plotter, design specifications engineer, display console graphics data input unit, printed cirsuit board designer, and a control computr) is presented. 85/12/31 86N26256

UTTL: Multivariable output control law design for the STOL (Short Takeoff and Landing) F-15 in landing configuration
AUTH: A/ACKER, B. H. CORP: Air Force Inst. of Tech., Wright-Patterson AFB, Ohio. CSS: (School of Engineering.)
ABS: Using the MULTI computer aided design and simulation program, multivariable, output feedback digital control laws are designed for the F-15 STOL aircraft in the landing configuration. The STOL F-15 landing configuration includes canards and reversible thrust in addition to conventional F-15 control surfaces. The additional controls allow decoupling of the output variables in the longitudinal plane. Longitudinal aircraft dynamics, derived from data provided by the prime contractor, McDonnell-Douglas, are presented in linearized state space form for the design procedure. Control laws are developed to stabilize the aircraft to perform longitudinal landing maneuvers (flight path control and flare) at six flight conditions. The design encompasses actuator dynamics, computational delay, sensor dynamics, sensor noise, and plant nonlinearities. Designs of two of the flight conditions are sufficiently insensitive to plant variations to be used at all but one of the remaining flight conditions. The technique of multivariable output feedback, with the MULTI program provides good robust designs for the STOL F-15.
RPT#: AD-A164516 AFIT/GE/ENG/85D-1 85/12/00 86N25340

UTTL: Study of the effects of discretizing quantitative feedback theory analog control system designs
AUTH: A/COUCOULES, J. S. CORP: Air Force Inst. of Tech., Wright-Patterson AFB, Ohio. CSS: (School of Engineering.)
ABS: This thesis examines the feasibility and a method of extending continuous domain Quantitative Feedback Theory (QFT) flight control system designs to the discrete domain. The results of two previous QFT analog design efforts are modified for a digital implementation. The first design effort is for the KC-135 transport aircraft. Robust analog fixed compensators are designed for three different flight conditions. The second design effort is for the AFTI/F-16 aircraft. In this design, parameter variation is due to both varying flight conditions and

different aircraft configurations caused by failed surfaces.
RPT#: AD-A164209 AFIT/GE/ENG/85D-10 85/12/00 86N25174

UTTL: An introduction to the application of Computer Aided Design (CAD) to the predesign of aircraft and the design of aircraft structures at the Aerospace Section
AUTH: A/BIL, C.; B/ROTHWELL, A. CORP: Technische Hogeschool, Delft (Netherlands). CSS: (Dept. of Aerospace Engineering.)
ABS: Equipment and software of a CAD plant are described and research in aircraft and aircraft structures design is surveyed. Possibilities to integrate an aircraft design and analysis system, the graphical design system MEDUSA, and GIFTS, a program generating calculation models from drawings of existing structures, are outlined. The aim is to create a pilot design system comparable with industrial CAD activities in the preconceptual phase.
RPT#: VTH-M-512 84/03/00 86N19045

UTTL: Inputting constructive solid geometry representations from two-dimensional orthographic engineering drawings
AUTH: A/BIN, H. PAA: A/(South China Institute of Technology, Guangzhou, China) CORP: Technische Hogeschool, Delft (Netherlands). CSS: (Dept. of Mathematics and Informatics.)
ABS: An approach to inputting geometric representations of three-dimensional objects via two-dimensional orthographic views is introduced. The user has to identify, from an engineering drawing, the primitive volumes such as cuboids, cylinders and spheres, from which a model of the object is constructed. The identified primitives have to be input. Their dimensions and transformation parameters are derived by the program from a set of points input via a digitizer from two or three views of the object on a single drawing. Set operations for combining the primitives are input separately. Based on this input, the system produces a Constructive Solid Geometry (CSG) representation of the object. Input of a CSG representation appears simpler for the user and for the system than input of the object via a boundary representation in terms of points, lines, and faces.
RPT#: REPT-84-49 84/00/00 86N16984

UTTL: Expert systems in engineering practice CORP: CIAD, Zoetermeer (Netherlands). CSS: (Projectgroep.)
ABS: The usefulness of artificial intelligence and particularly expert systems for computer aided design support, was investigated. The DELFI expert system was tested. Using the results of this test, DELFI was redesigned, providing possibilities of iteration, calling external calculation routines, initialization of fixed data into a base, and graphical reproduction. Design rules are framed as input for the DELFI program. A design process is made, to investigate phases and operations in which an expert system is useful.
RPT#: ISBN-90-6818-018-5 85/06/00 86N15977

UTTL: ADS: A FORTRAN program for automated design synthesis: Version 1.10
AUTH: A/VANDERPLAATS, G. N. CORP: California Univ., Santa Barbara.
ABS: A new general-purpose optimization program for engineering design is described. ADS (Automated Design Synthesis - Version 1.10) is a FORTRAN program for solution of nonlinear constrained optimization problems. The program is segmented into three levels: strategy, optimizer, and one-dimensional search. At each level, several options are available so that a total of over 100 possible combinations can be created. Examples of available strategies are sequential unconstrained minimization, the Augmented Lagrange Multiplier method, and Sequential Linear Programming. Available optimizers include variable metric methods and the Method of Feasible Directions as examples, and one-dimensional search options include polynomial interpolation and the Golden Section method as examples. Emphasis is placed on ease of use of the program. All information is transferred via a single parameter list. Default values are provided for all internal program parameters such as convergence criteria, and the user is given a simple means to over-ride these, if desired.
RPT#: NASA-CR-177985 NAS 1.26:177985 85/09/00 86N11894

UTTL: Computational structural mechanics: A new activity at the NASA Langley Research Center
AUTH: A/KNIGHT, N. F., JR.; B/STROUD, W. J. CORP: National Aeronautics and Space Administration. Langley Research Center, Hampton, Va. Presented at 22nd Ann. Tech. Meeting of the Soc. of Eng. Sci., University Park, Pa., 7-9 Oct. 1985
ABS: Complex structures considered for the late 1980's and early 1990's include composite primary aircraft structures and the space station. These structures are

much more difficult to analyze than today's structures and necessitate a major upgrade in computerized structural analysis technology. A major research activity in computational structural mechanics (CSM) was initiated. The objective of the CSM activity is develop advanced structural analysis technology that will exploit modern and emerging computers such as computers with vector and/or parallel processing capabilities. The three main research activities underway in CSM include: (1) structural analysis methods development; (2) a software testbed for evaluating the methods; and (3) numerical techniques for parallel processing computers. The motivation and objectives of the CSM activity are presented and CSM activity is described. The current CSM research thrusts, and near and long term CSM research thrusts are outlined.
RPT#: NASA-TM-87612 NAS 1.15:87612 85/09/00 86N11540

UTTL: MBB expands CADAM system for a 320 program
CORP: Joint Publications Research Service, Arlington, Va.
ABS: The use of computers in aircraft design in West Germany is discussed. Monitor screens are used extensively in computer aided design or the European Airbus. Time gain in drafting and drafting modifications is an important feature. 84/09/25 85N29099

UTTL: Active Control Systems: Review, Evaluation and Projections CORP: Advisory Group for Aerospace Research and Development, Neuilly-Sur-Seine (France). Symp. held in Toronto, 15-18 Oct. 1984
ANN: Numerous topics relative to digital flight control systems are discussed. Active control technology applications, optimization of systems architecture for both reliability and costs control cam design, handling qualities, and the operational demonstration of systems reliability are among the topics covered. For individual titles see N85-27884 through N85-27911.
RPT#: AGARD-CP-384 ISBN-92-835-0375-9 AD-A155853 85/03/00 85N27883

UTTL: The application of computer aided structural optimization to the design of aircraft components
AUTH: A/WELLEN, H. CORP: Messerschmitt-Boelkow-Blohm G.m.b.H., Bremen (West Germany). Presented at DGLR-Fachausschusssitzung Festigkeit u. Bauweisen, Neubiberg, West Germany, 5 Jul. 1984
ABS: The Structural Analysis and Redesign System (STARS) program system was used for computer aided structural optimization of aircraft components. Practical use and results, present status, and planned extension of STARS are described. The application of computer aided structural optimization is demonstrated using the inner Airbus A-310 trailing-edge flaps. Computer aided structural optimization offers the possibility of automatic weight-optimal dimensioning of carrying parts using programmed, mathematical methods. The weight optimum leads to time-and cost advantages.
RPT#: MBB-UT-21/84-0 84/00/00 85N27728

UTTL: Computer software for aerodynamic design of aircraft developed within the National Aerospace Laboratory
AUTH: A/ENDO, H. CORP: National Aerospace Lab., Tokyo (Japan).
ABS: A computer was first introduced to the National Aerospace Laboratory in 1960. Subsequent introduction of increasingly more sophisticated models played important roles in the active research conducted by the laboratory. Acquisition of FACOM 230-75AP, the first vector computer in Japan, resulted in the start of software designing for full utilization of a large, ultra-high speed computer. The analytical programs developed by the laboratory include FLOW, PNCCP, TSFOIL, AFMESH, NSFOIL, SPWING, and AFPWING, while notable design programs are TSFD, INVERSE, SPWD, and BLAY. In designing these softwares, the laboratory is aware of importance of organizing joint projects to avoid unnecessary expenditures and waste of manpower, confirmation of reliability of each program, systematization of data bases, and publication of these programs for the general interest. A computer specially designed for statistical simulation of a wind tunnel is described. With the completion of the next generation numerical simulator, such a computer wind tunnel system is expected to play an important role in aircraft technology in Japan. 83/00/00 85N26613

UTTL: Multivariable control law design for the AFTI/F-16 with a failed control surface
AUTH: A/ESLINGER, R. A. CORP: Air Force Inst. of Tech., Wright-Patterson AFB, Ohio. CSS: (School of Engineering.)
ABS: Two linearized models containing coupled aircraft equations are developed for the AFTI/F-16. The first is a model of the healthy aircraft with all control surface intact, and the second is a model of the aircraft with a free-floating right horizontal tail and all other surfaces operational. The multivariable design technique of Professor Brian Porter and the

computer program MULTI are first used to design control laws for the healthy model. The control laws are tailored to perform seven maneuvers at four flight conditions. Maximum maneuvers are commanded to yield maximum control surface deflections. The same control law designs are then applied to the model with a failed right horizontal tail, and the performance is evaluated. Some maneuvers require modifications to the designs or lowered maximum maneuver requirements to avoid overshooting the deflection limits of the operational control surfaces. Simulation responses are presented for both the healthy and failure aircraft models. Generally, when the right horizontal tail fails, the left horizontal tail assumes primary pitch control and the flaperons take over complete roll control. The flaperons, rudder, and canards deflect to counter the rolling and yawing moments produced by the left horizontal tail deflection.

RPT#: AD-A151908 AFIT/GE/ENG/84D-28 84/12/00 85N25271

UTTL: Description of MBB computerized design techniques for A320 CORP: Joint Publications Research Service, Arlington, Va.

ABS: The design of aircrafts by computerized design techniques is discussed. Picture screen, light marker, and computers are now exclusively the means by which the new Airbus A320 aircraft is built. Complete major structural parts, components, metal and synthetic material structures, down to the smallest sheet metal parts and connection elements are drawn on the picture screen, the drawing data are stored in computers, they are preserved on magnetic tape for use as construction documents, and they are reproduced on microfilm or they are printed out on paper. 85/01/02 85N17194

UTTL: The Influence of Large Scale Computing on Aircraft Structural Design CORP: Advisory Group for Aerospace Research and Development, Neuilly-Sur-Seine (France). Meeting held in Sienna, Italy, 2-6 Apr. 1984

ANN: Advances in large scale computing capacity and how they affect aeronautical design are reported. The use of vector processing to solve aircraft structural problems, the influence of new computing systems on computational mechanisms, and use of artificial intelligence in design processing is discussed. The role of AGARD and its response to the challenge is examined. For individual titles see N85-10041 through N85-10043.

RPT#: AGARD-R-706 ISBN-92-835-0364-3 84/08/00 85N10040

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Advisory Group for Aerospace Research and Development, NATO
INTEGRATED DESIGN OF ADVANCED FIGHTERS
Published May 1987
216 pages

The recent AGARD Short Course on "Fundamentals of Fighter Aircraft Design", presented at the Von Karman Institute for Fluid Dynamics on February 17—21 1986, and in Greece and Turkey, considered the various aspects of aerodynamics. The present lecture series provides a general overview of the "state-of-the-art" in modern fighter design, with an introduction to the innovations of "Computer-Aided Design Evaluation" to both

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After the introduction reviewing the evolution of the modern fighter aircraft the Lecture Series will continue to develop the various stages of the total design problem. The integration of requirements into the preliminary configuration of the design will be followed by discussions of modern design techniques that are currently used to assess and validate the evolving configuration.

The second day will consider the overall integration process as applied to various current design challenges including multi-rôle aircraft, shipborne operator and VSTOL and STOVL concepts. The lecturers include two engineering qualified pilots who will contribute their experiences in development flying of several current single and twin engine fighters of both US and European origin. They will continue to present their perceptions of future military needs and resulting design trends.

All lecturers will contribute to a final Round Table Discussion.

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